

Beauty and Charm Production

at the Fermilab Tevatron

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Fermi National Accelerator lab

b quark discovered - 1977

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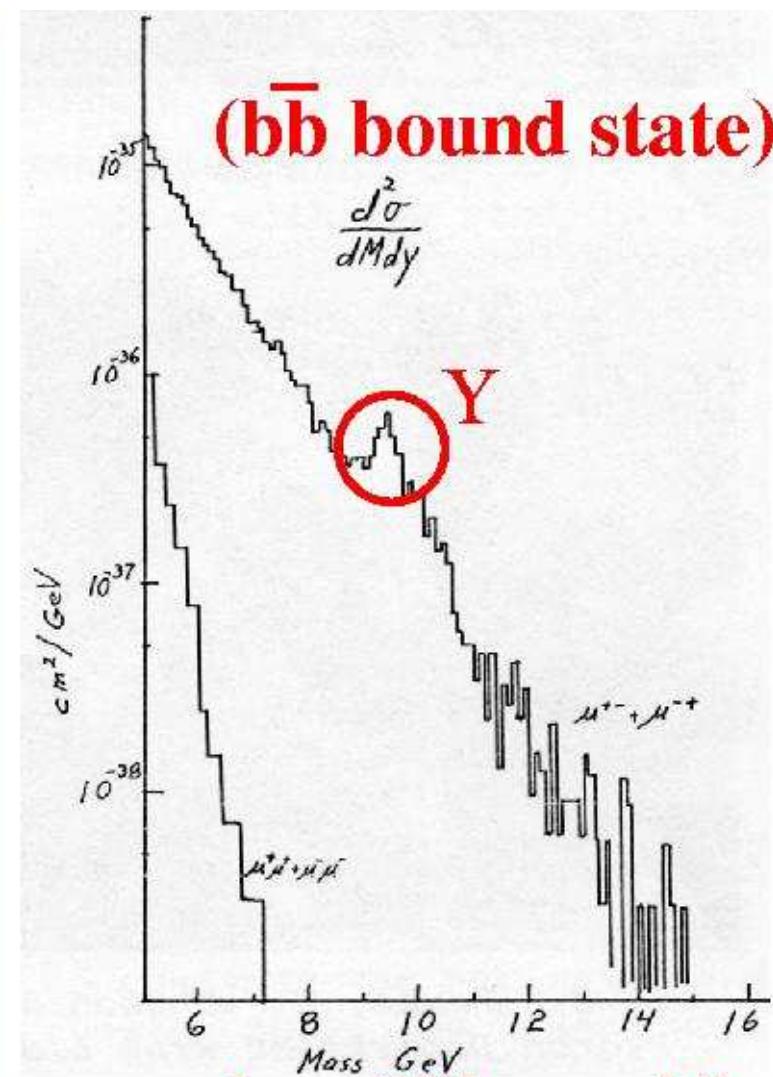
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An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 6.5 GeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of sub-nuclear particles.

The speculation that all matter is made up of small point-like objects called "quarks" has been hotly pursued in research centers all over the world in the past few years. The original theories suggested the existence of three different kinds of quarks. The "J/psi" particles discovered at the Brookhaven National Laboratory and the Stanford Linear Accelerator Center in 1974 were the first of several discoveries which showed strong evidence of the existence of a fourth kind of quark, the "charmed" quark. It now appears as a result of the work at Fermilab that there may be a fifth quark, still another constituent in the fundamental structure of matter.

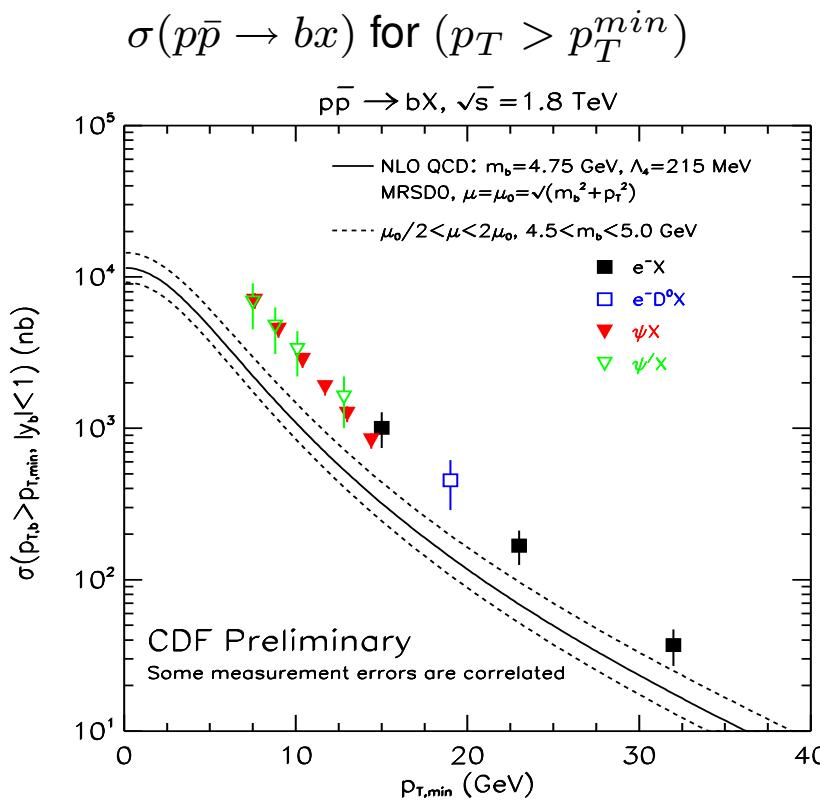
...MORE

"It now appears that there may be a fifth quark"



20 years later....

- In Run I only a small portion of the b hadron inclusive cross-section, $p_T > 6.0 \text{ GeV}/c$, was measured.



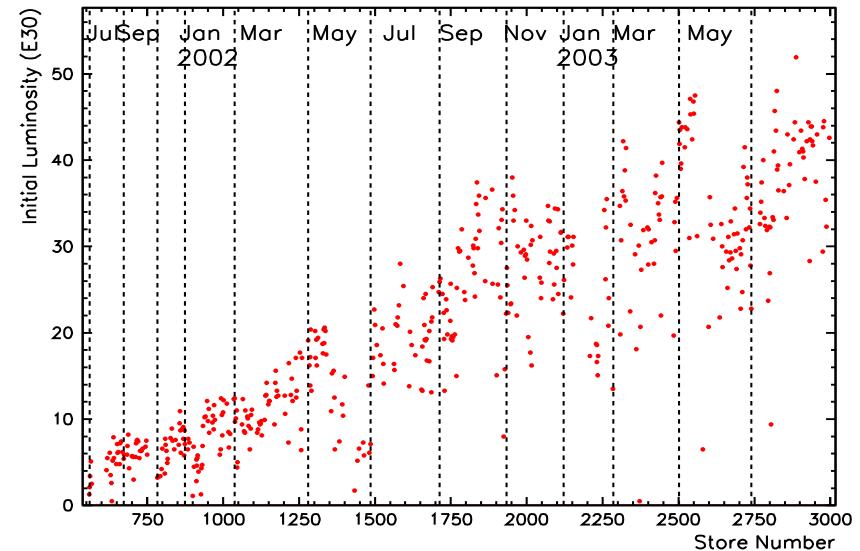
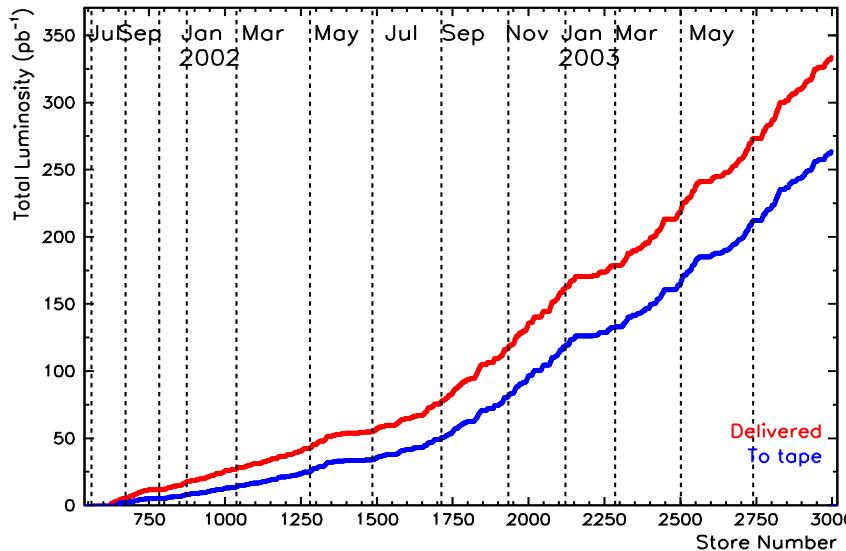
- In 1997, b production cross-sections were still $> 2 \times$ larger than QCD predictions.
- Theory and data could be forced to agree by using extreme values of renormalization and factorization scales (*tweakable parameters in the theory*).

Is this a shape or normalization problem? What about charm?

The Tevatron Today

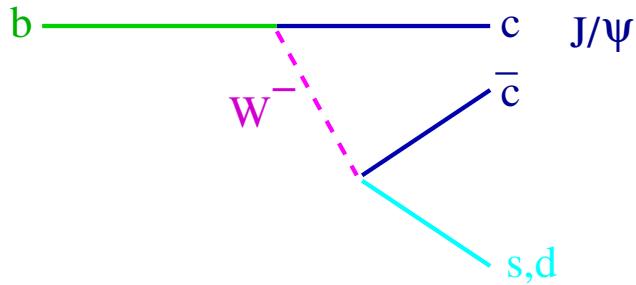
- In 1985, Tevatron collider begins operating @ $\sqrt{s} = 1.6 \text{ TeV}$
- Run I of the Tevatron collected collider data at $\sqrt{s} = 1.8 \text{ TeV}$ from 1992-1995. $\sim 109 \text{ pb}^{-1}$ of data was collected by the 2 collider detectors with $\mathcal{L}^{typical} = 1.6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

Run II : Summer 2001 - present. 2.5X more data already!



Outline

- Overview of the theoretical basis of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Description of the Run II CDF detector at the Tevatron.

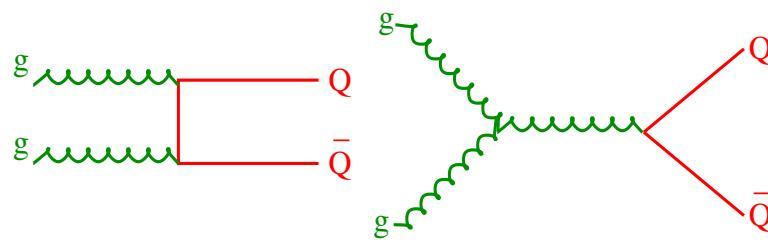


Count b 's by counting J/ψ s

- Run II measurement of the *inclusive central J/ψ* cross-section down to $p_T = 0$.
- Run II measurement of the *inclusive central b -hadron* cross-section *using* $b \rightarrow J/\psi X$ down to $p_T = 0$.
- Run II measurement of the charm meson cross-sections.

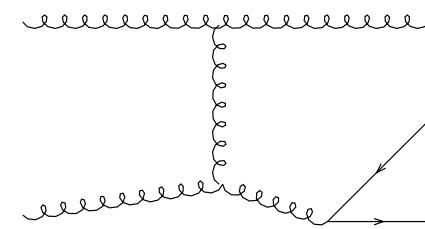
THE THEORY

Heavy Quark Production in $p\bar{p}$

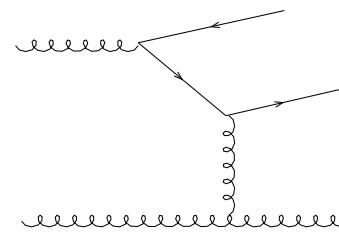


LO Heavy Quark Production

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}}$$

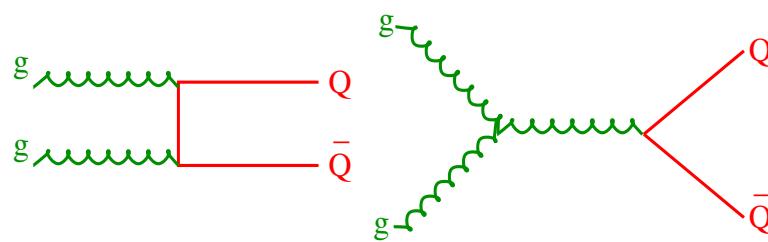


NLO: Gluon splitting

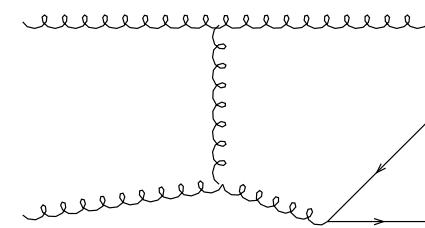
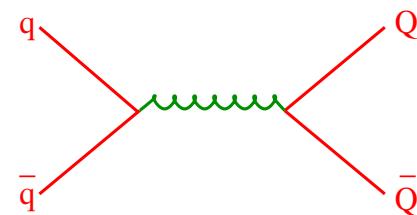


NLO: Flavour excitation

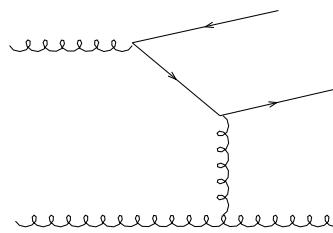
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



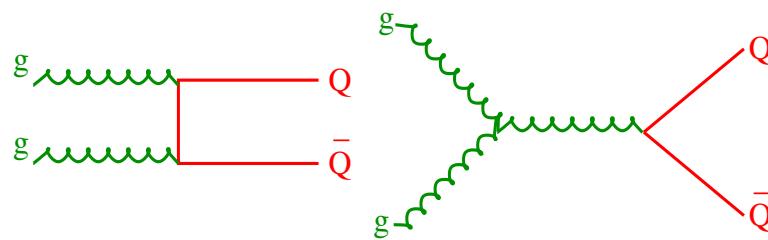
NLO: Gluon splitting



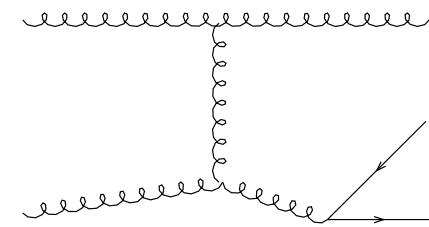
NLO: Flavour excitation

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \text{Proton structure}$$

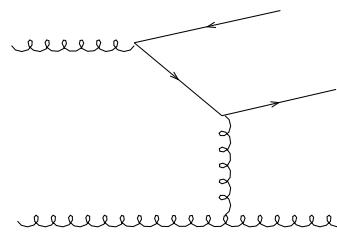
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



NLO: Gluon splitting



NLO: Flavour excitation

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}}$$

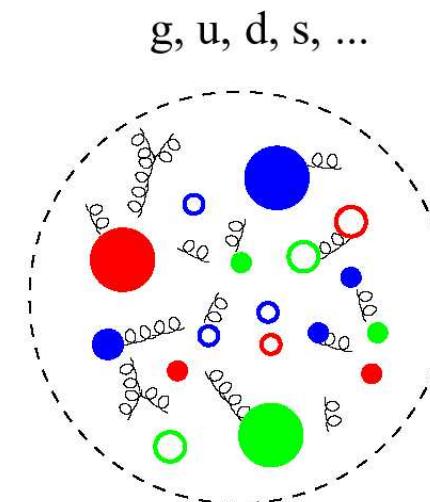
\otimes

$f_{p,\bar{p}}$
Proton structure

$$\otimes \underbrace{\begin{array}{c} D^{b \rightarrow B} \\ \text{fragmentation} \end{array}}_{\text{observed}} = \underbrace{\frac{d\sigma(p\bar{p} \rightarrow BX)}{dp_T(B)}}_{\text{observed}}$$

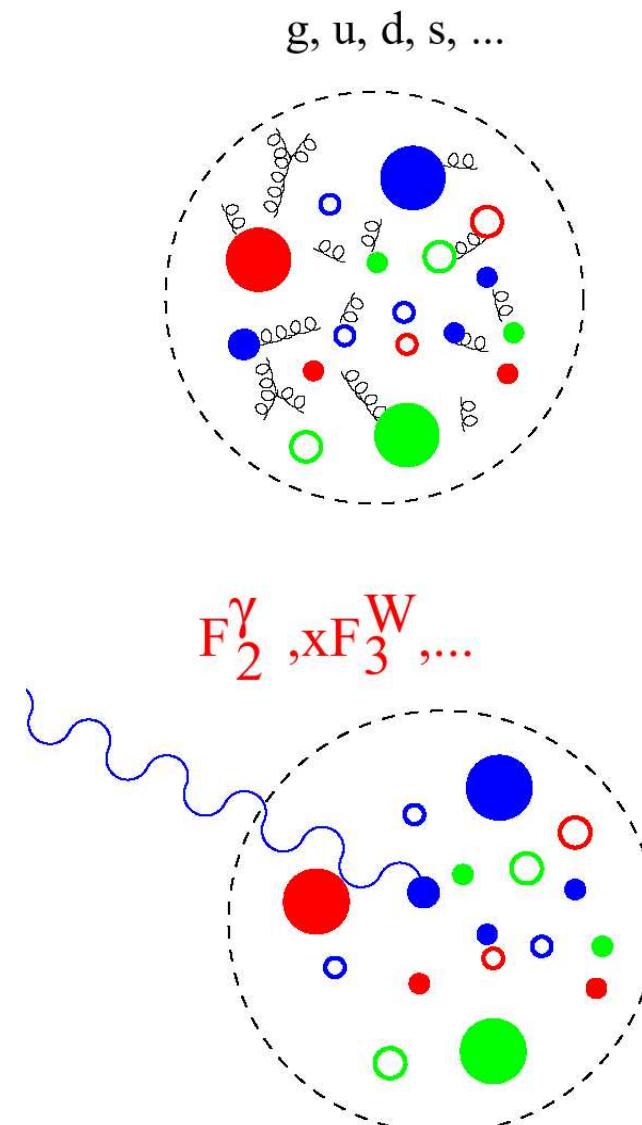
Modeling proton structure

- Quark production cross-sections in $p\bar{p}$ collisions depend on quark/gluon/sea distributions in the proton.



Modeling proton structure

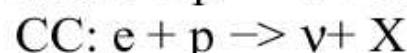
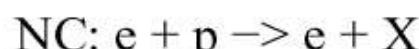
- Quark production cross-sections in $p\bar{p}$ collisions depend on quark/gluon/sea distributions in the proton.
- Proton structure needs to be probed experimentally.



Probing proton structure

$e/\mu/\nu$ used to probe *Proton Structure:*

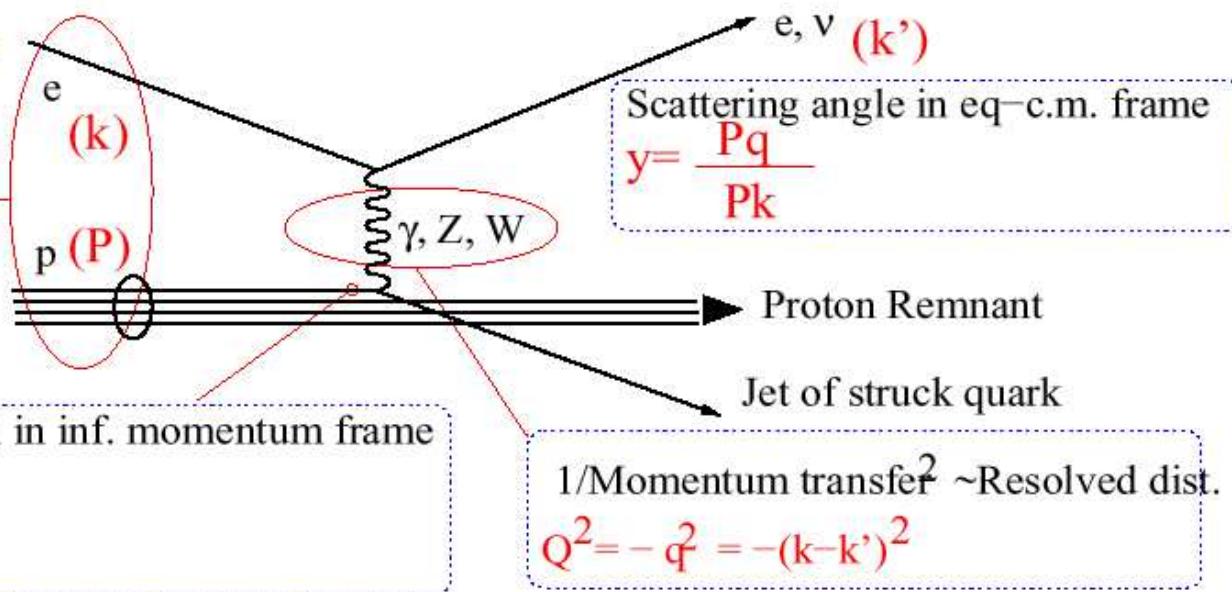
Reactions:



Lorentz invariants:

e p-c.m.-
energy: \sqrt{s}

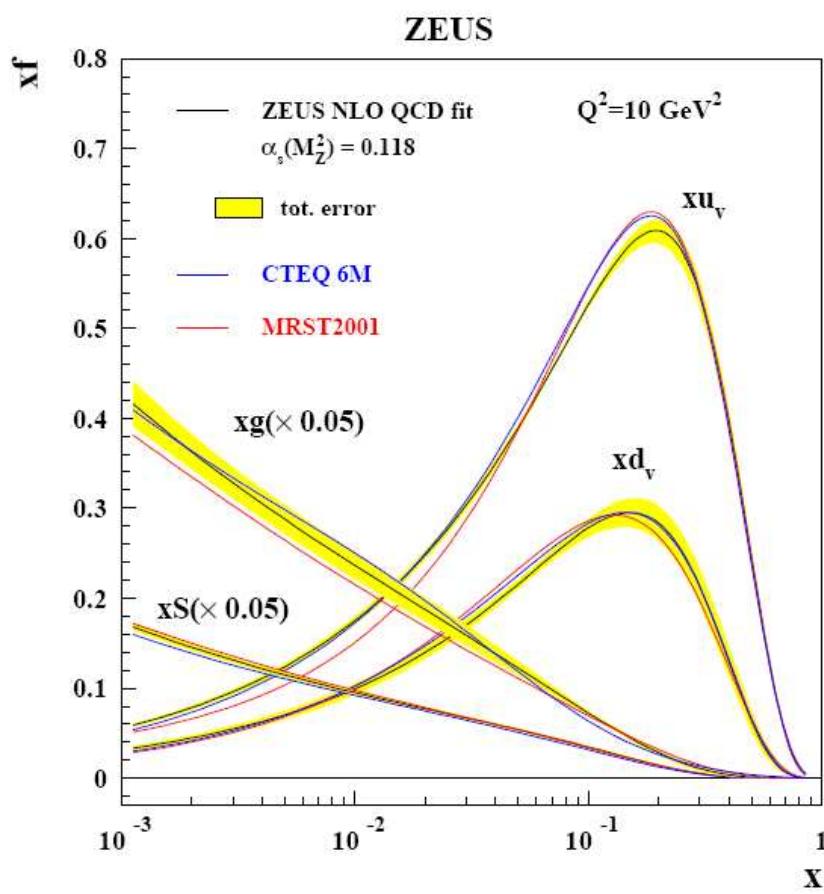
$$s = (P+k)^2$$



Relation:

$$Q^2 = s x y \quad (M_p \ll P)$$

Parton Density Functions (PDF)

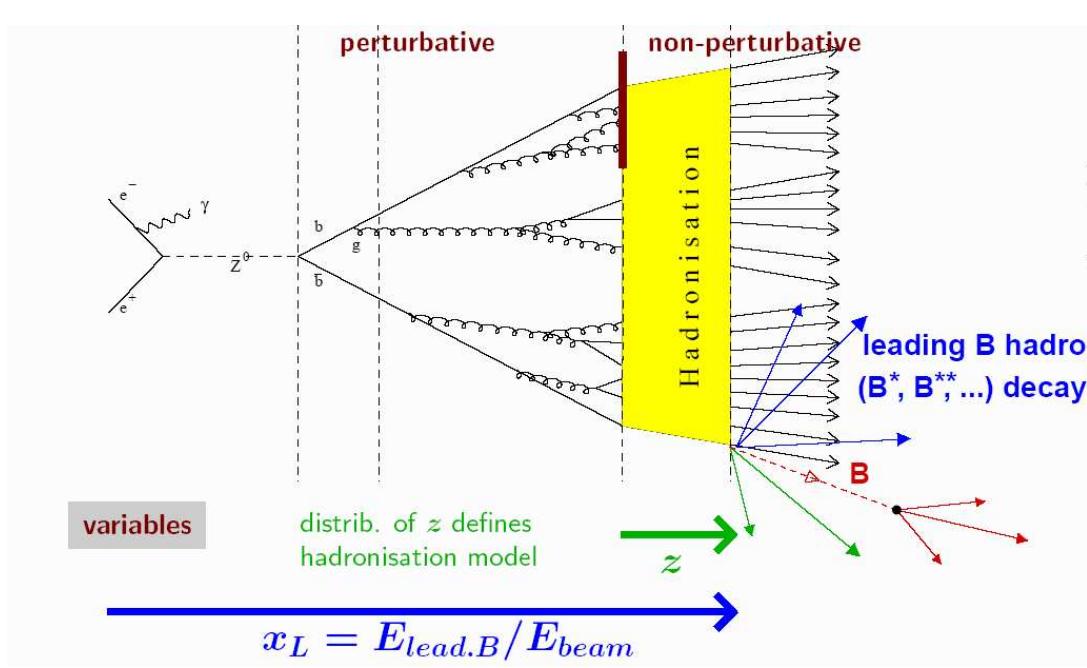


Parton densities with errors extracted from fits to the data

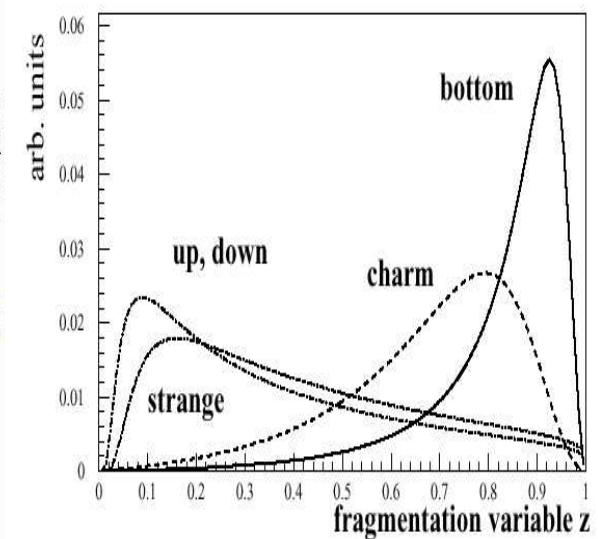
- *Proton Structure Functions* depend on the measuring process. Different experiments probe different ranges of x , different partons...etc
- *PDFs* ($x f(x, Q^2)$) are global fits to data on proton structure that are independent of the measurement process but *depend on factorization scheme chosen*.

Fragmentation Functions

- b/c - quarks fragment to hadrons, H_b .
- $D^{meas}(x) = \int \underbrace{D^{pert}(x')}_{pQCD/MC} \otimes \underbrace{D^{non-pert}(x')}_{Parameterized/MC} dx'$



Peterson parameterization

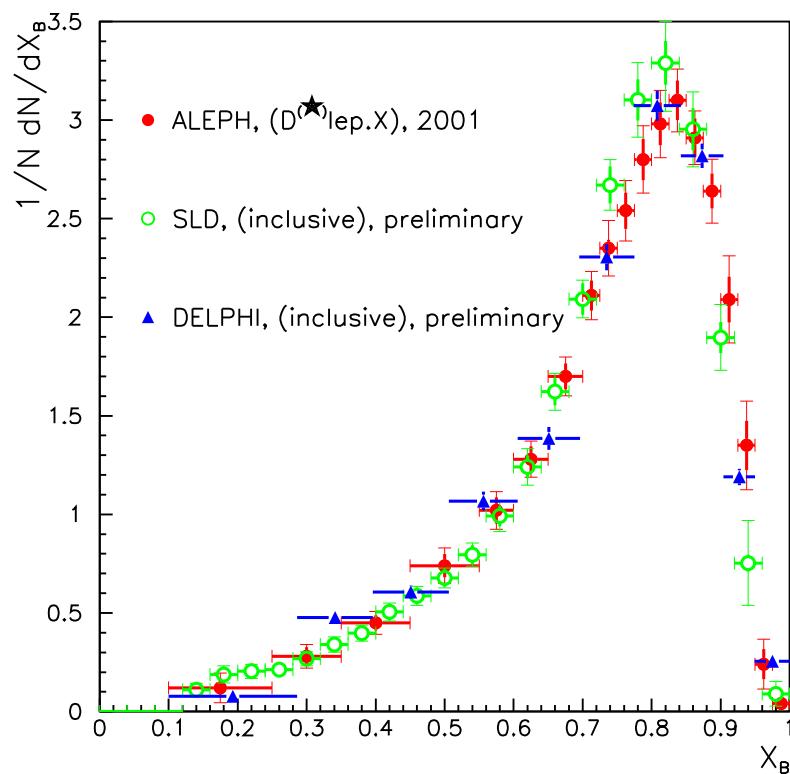


$$z = \frac{(E+p_{||})_{hadron}}{(E+p)_{quark}}$$

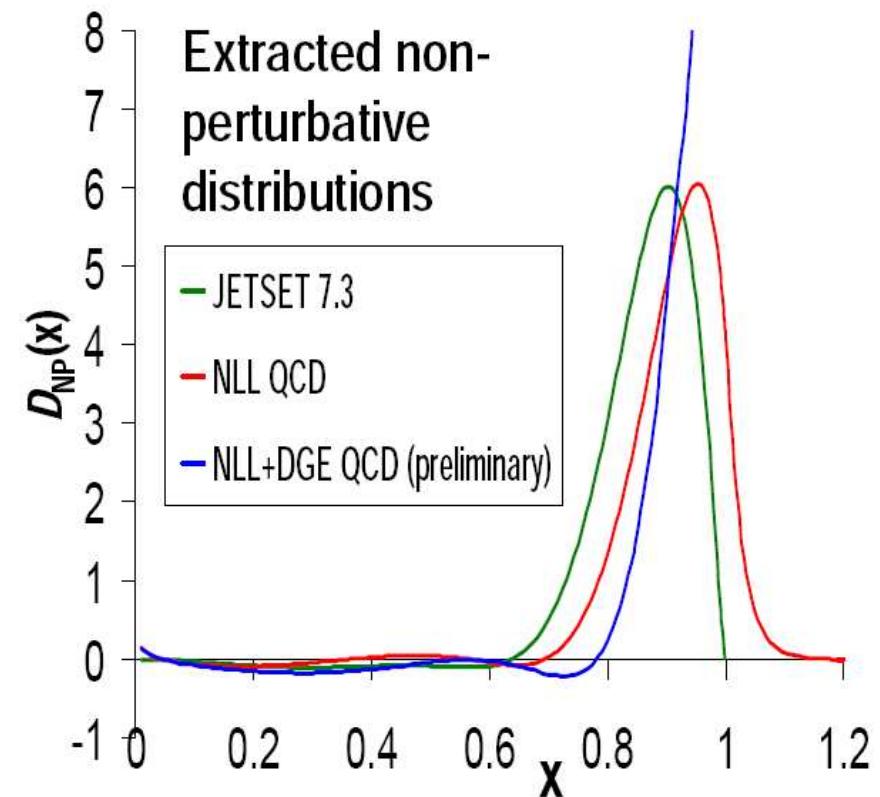
Recent Theory Advances

- In pQCD calculation, powers of $\alpha_s \log p_T/m_Q$ modify **shape** of fragmentation function. When $p_T \gg m_Q$ logarithms large \Rightarrow large corrections needed. Next-to-Leading-log resummations performed in 2001. *Important for predicting Tevatron heavy quark cross-section shapes at high p_T .*
- New approach: Moment analysis (Cacciari *et. al.* - 2002)
 - Transformation: $\tilde{D}(N) = \int x^{N-1} D(x) dx \rightarrow$ moment space
 - $\tilde{D}^{meas}(N) = \underbrace{\tilde{D}^{pert}(N) \times \tilde{D}^{non-pert}(N)}_{\text{A product}}$

Measured Fragmentation Fncns.



$D(x)$ Measured



$D^{non-pert}(x')$ Extracted

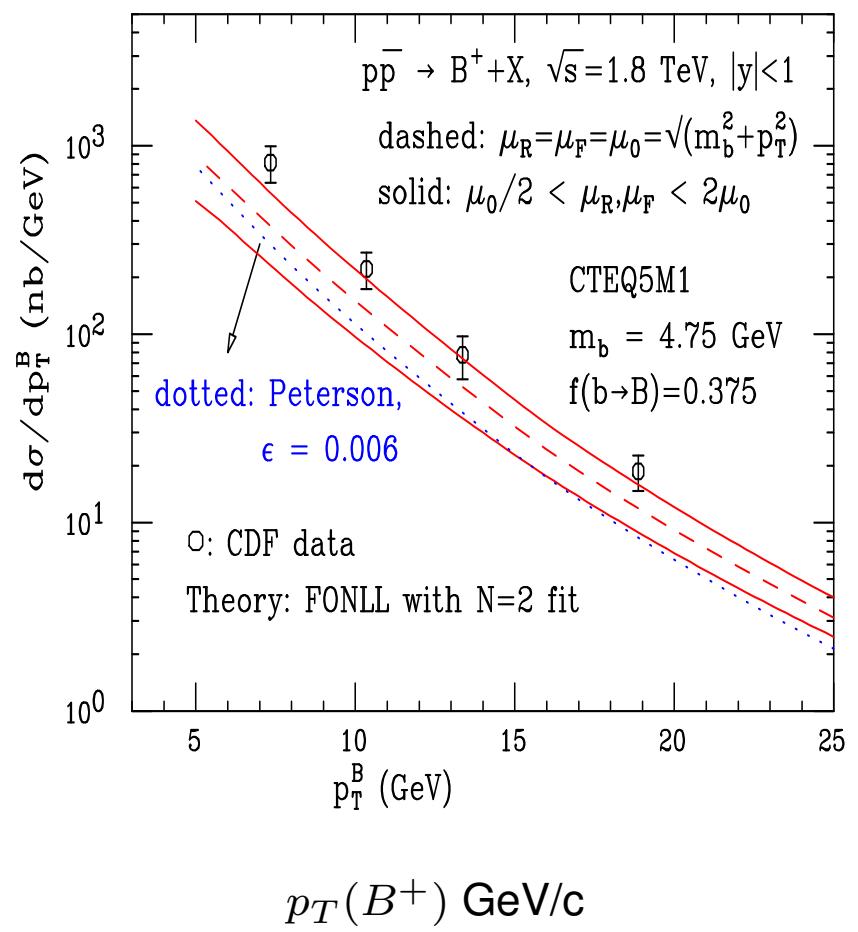
Non-perturbative functions used must match perturbative assumptions

Comparison with Run I Data - NLL

Resummation of next-to-leading logs merged with the QCD NLO using the method of moments instead of a fragmentation model \Rightarrow Better agreement with CDF Run I data on B meson cross-sections (for $p_T > 5.0 \text{ GeV}/c$).

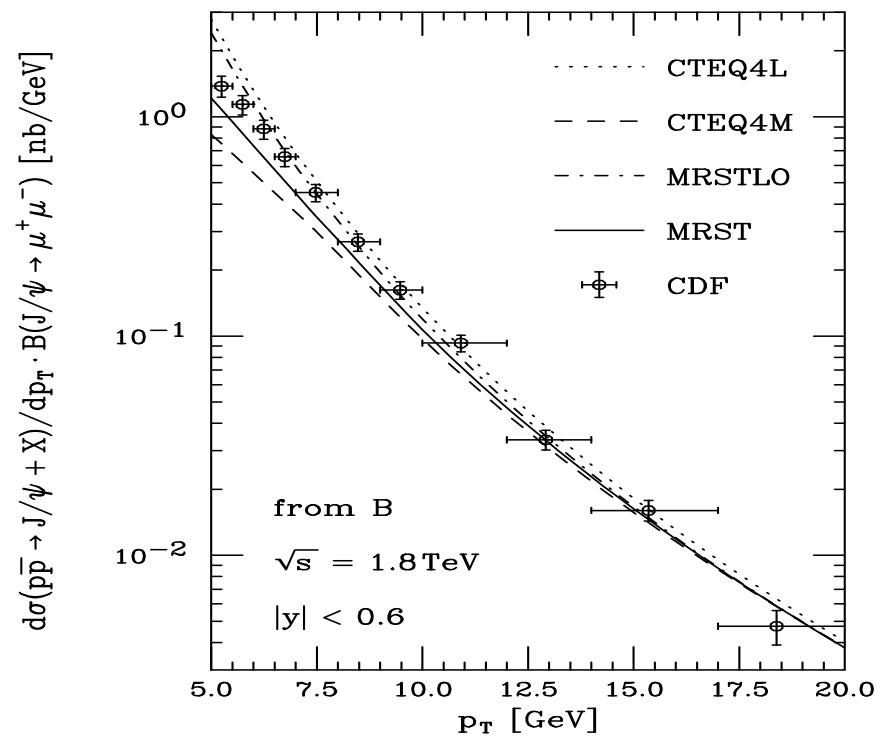
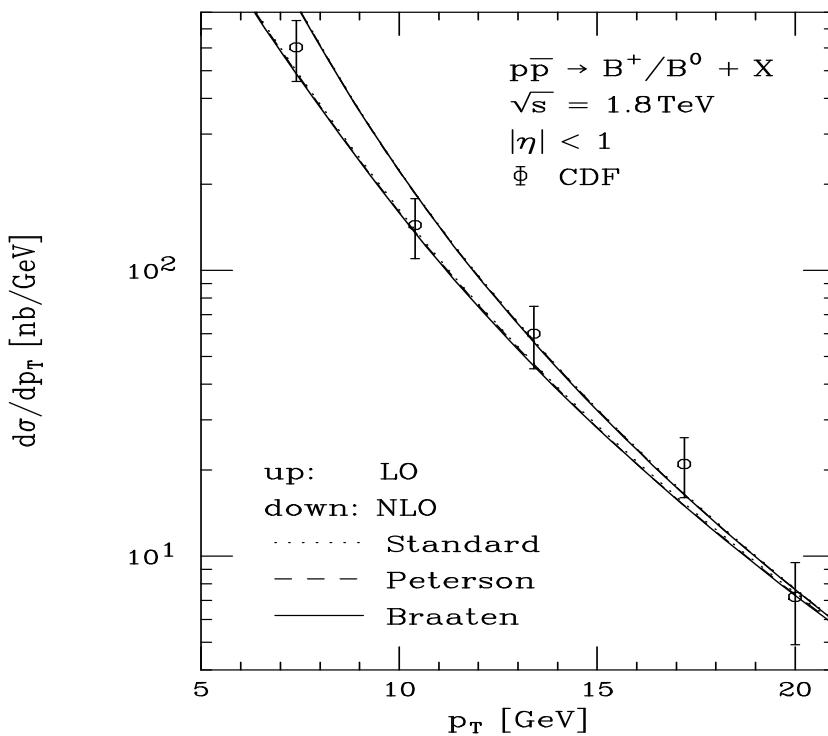
Cacciari, Nason hep-ph/0204025 (Run I)

$d\sigma(p\bar{p} \rightarrow B^+ X)/dp_T$ vs $p_T(B^+)$



Alternatives to FONLL

Non-perturbative fragmentation functions for B mesons are extracted from recent LEP data using 3 different parameterizations. used with \bar{MS} factorization scheme.



Binnewies, Kniehl, Kramer hep-ph/9802231 (Run I)

hep-ph/9901348 (Run I)

Theory Summary

- Parton distribution functions and fragmentation functions based on fits to experimental data are needed in addition to NLO QCD calculations to determine b cross-sections.
- Phenomenological fits to the non-perturbative part of the fragmentation function must be done in a manner consistent with the QCD calculation of the perturbative part.
- Agreement with the Run I spectrum for $p_T > 5.0 \text{ GeV}/c$ has improved mainly due to advances in the theoretical modeling of the b fragmentation.

Total cross-sections do not depend on the

fragmentation model! = powerful experimental test.

THE DETECTOR

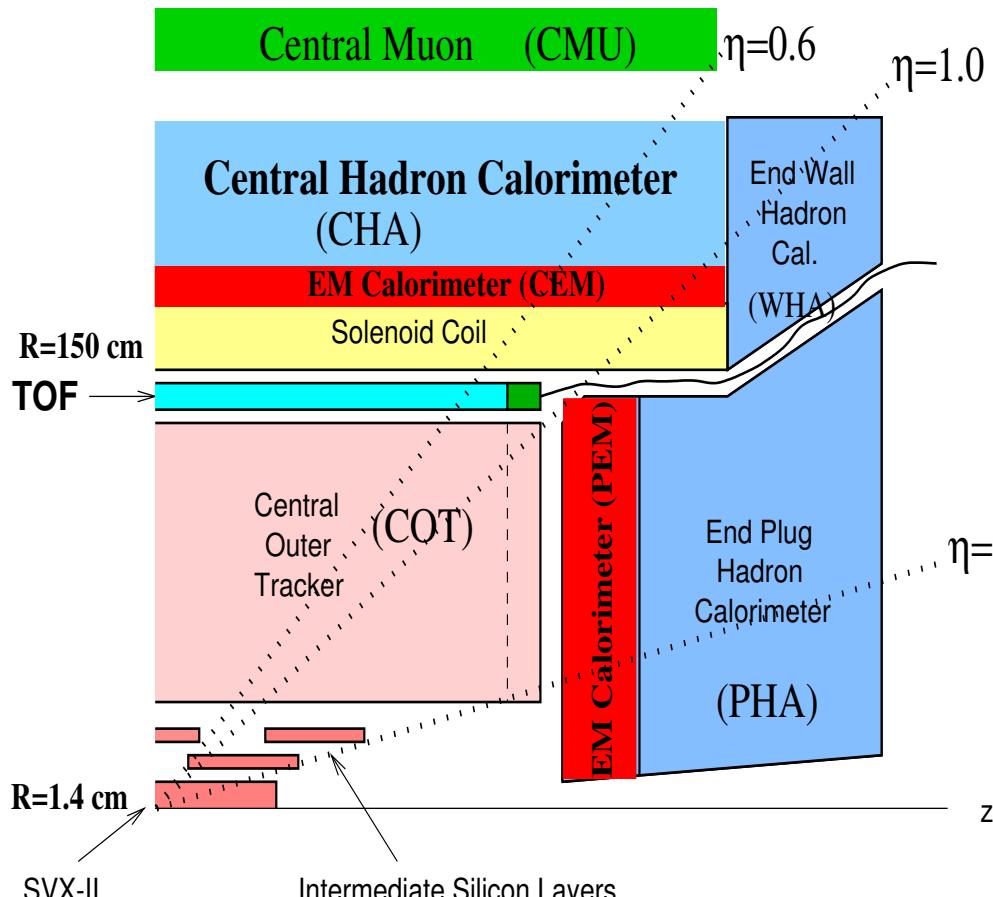
The Collider Detector at Fermilab

Run II: 788 collaborators, 62 institutions, 12 countries



CDF Run II - Overview

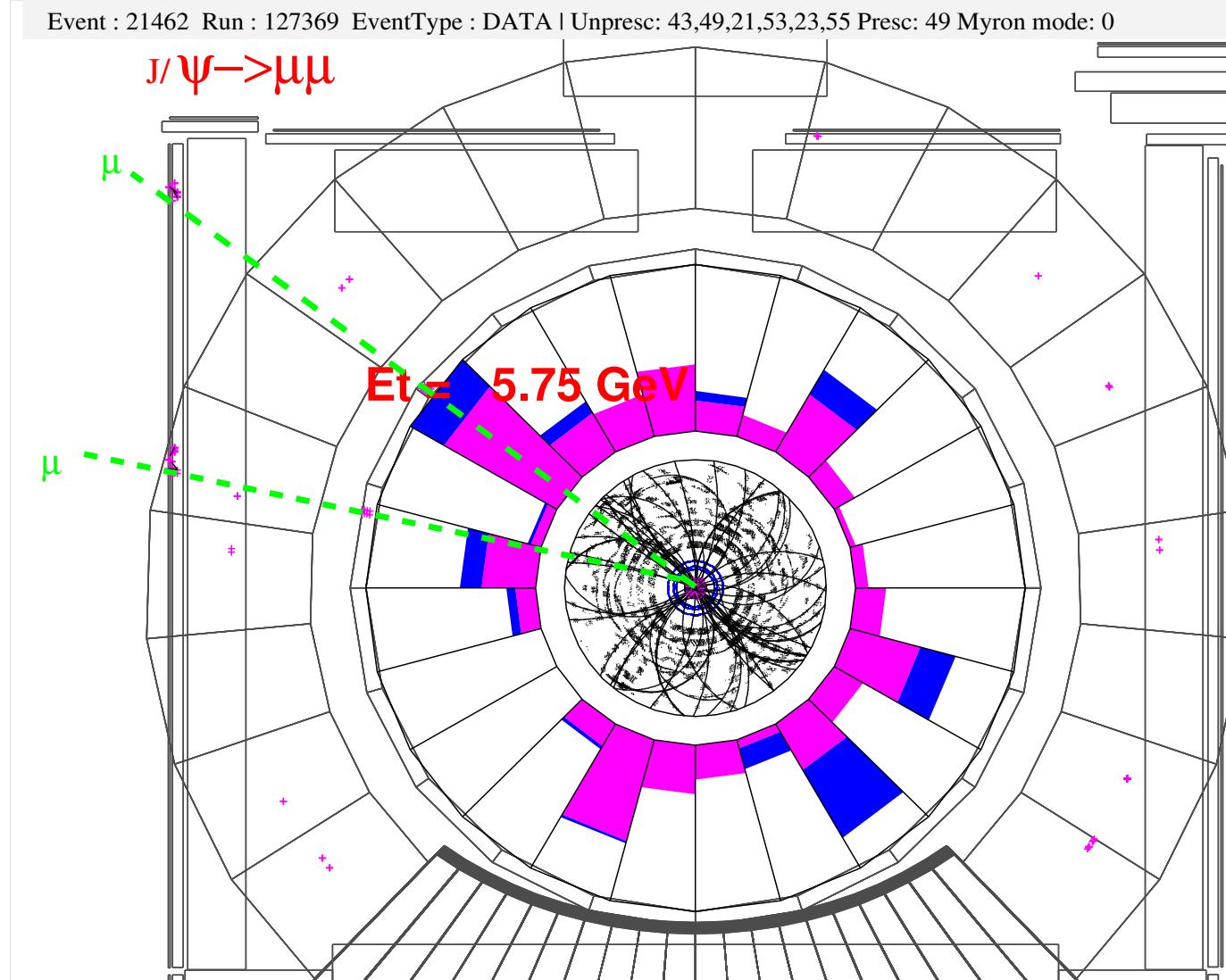
Signals: $J/\psi \rightarrow \mu\mu$, $D \rightarrow K\pi$, displaced b vertices



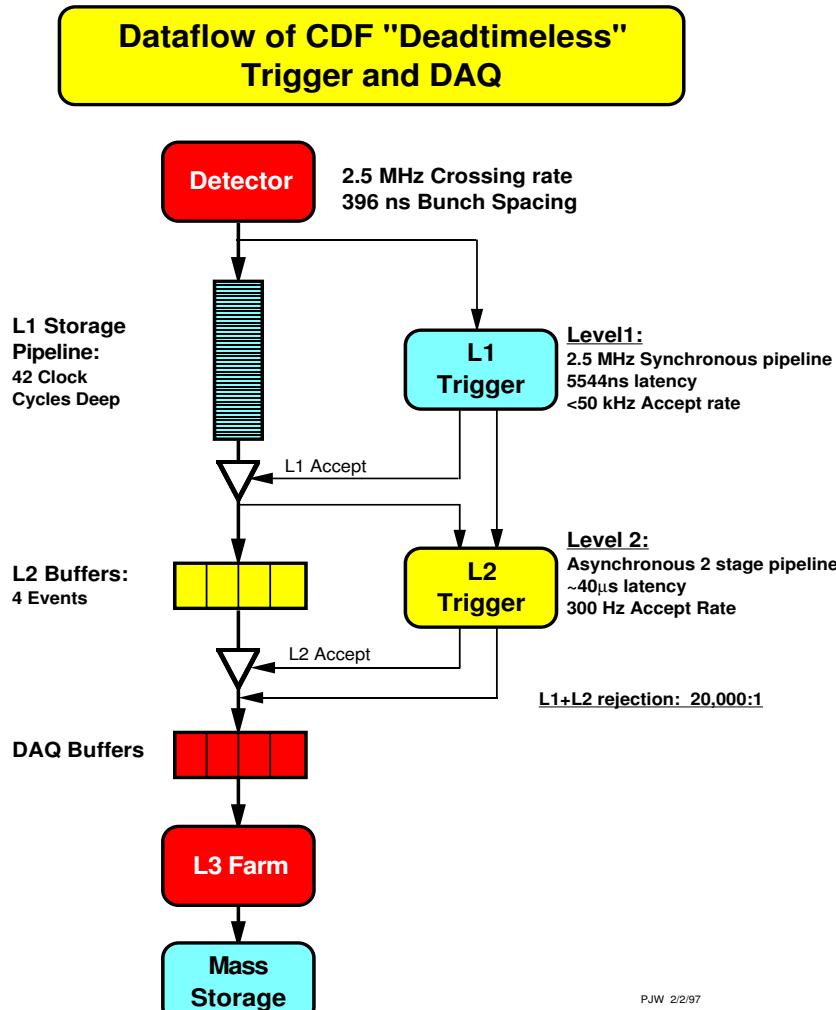
$$\eta = -1/2 \ln \tan \theta/2$$

- **96 layer COT:** $\sigma(p_t)/p_t = 0.003p_t$
- **Silicon vertex detector:** 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 20\mu m$
- **Central Muon detector:** Prop. counters outside central calor. 5.5 π interaction lengths.

Event Snapshot - $J/\psi \rightarrow \mu\mu$



CDF Data Flow



$250 \text{ pb}^{-1} \Rightarrow 480 \text{ TB on tape}$

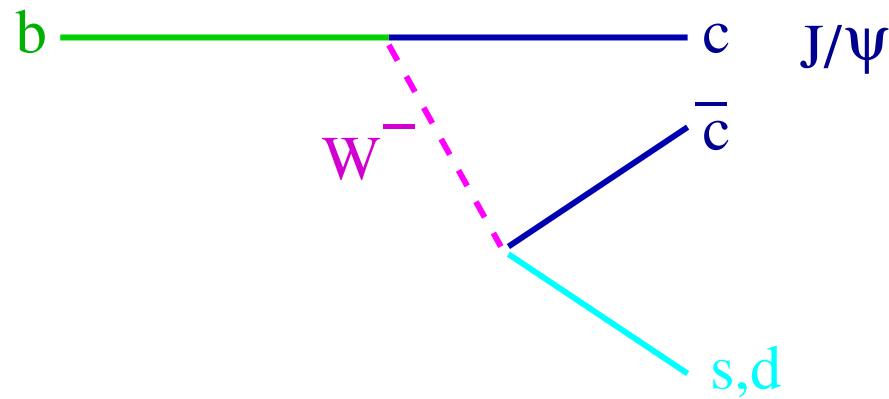
L1 latency: Pipeline depth = L1 processing time $\sim 5\mu\text{secs}$.

The SVXII detector is readout on L1 Accept.

L2 processing time: The Silicon Vertex Trigger is in L2 \Rightarrow *readout of the Silicon takes place in $\sim 15\mu\text{secs} + \sim 15\mu\text{secs}$ SVT processing time*

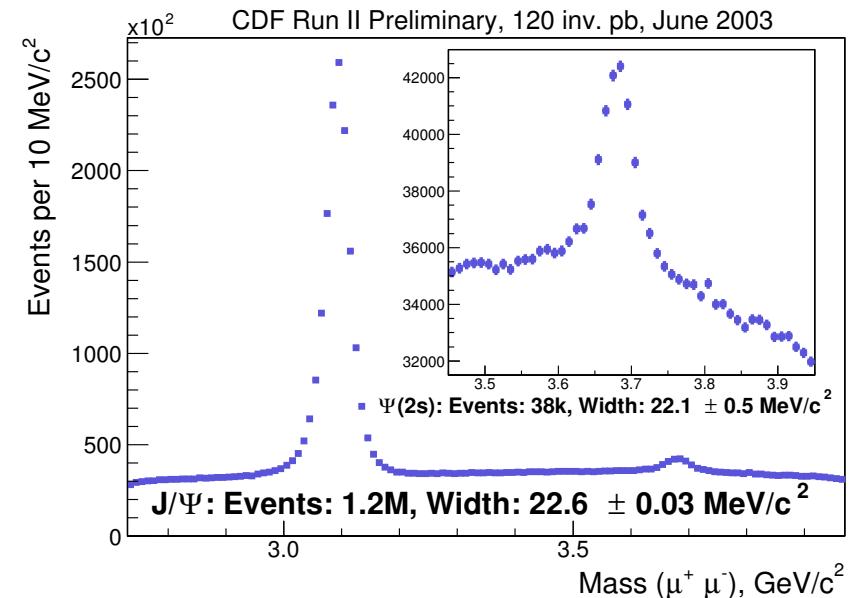
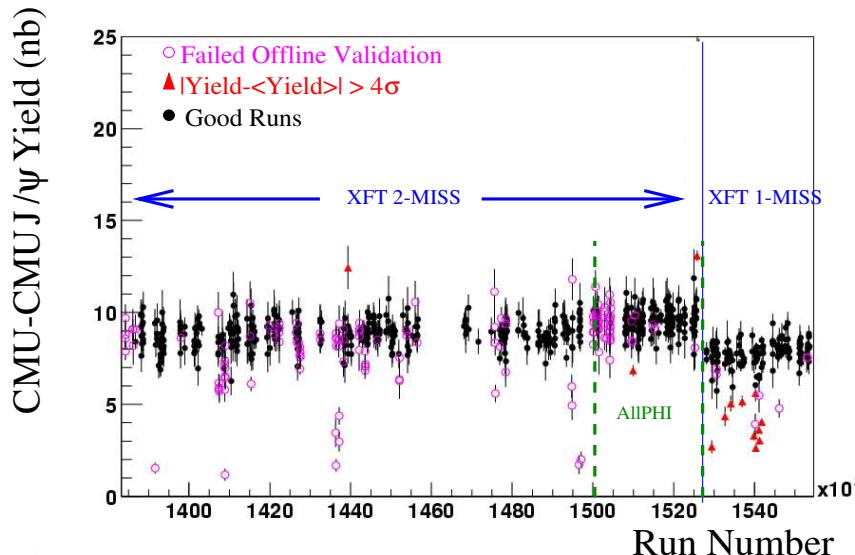
Data logging rate: sustained rate of 18MB/s

RUN II MEASUREMENT OF THE J/ψ and b -hadron inclusive cross-sections

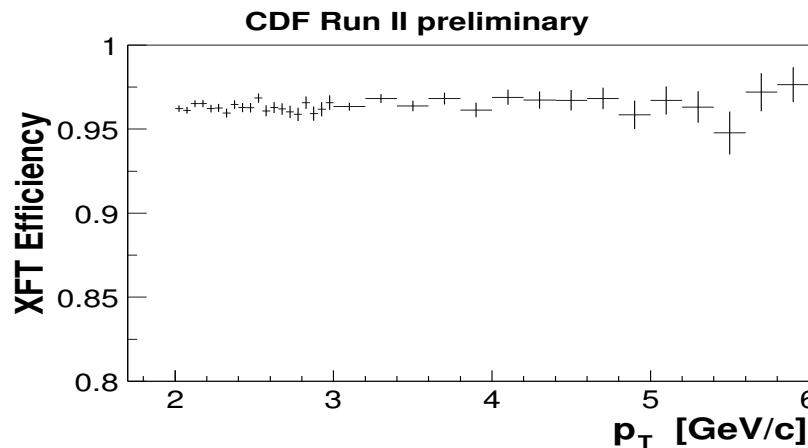


L1 Muon triggers (CDF)

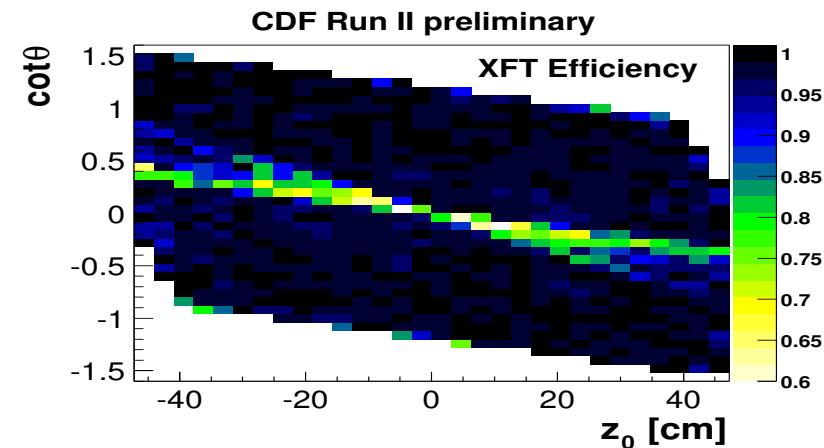
- Tracks are reconstructed in the COT by the Level 1 Trigger eXtra Fast Tracker (XFT). A match is made to hits in the Central Muon Chambers.
- lower p_t reach: $p_t(\mu) > 1.5(|\eta| < 0.6), 2.0(0.6 < |\eta| < 1.0)$*
 $\rightarrow p_t(J/\psi) = 0 \text{ GeV}/c \rightarrow \text{TOTAL cross-sections in } |y| < 0.6.$



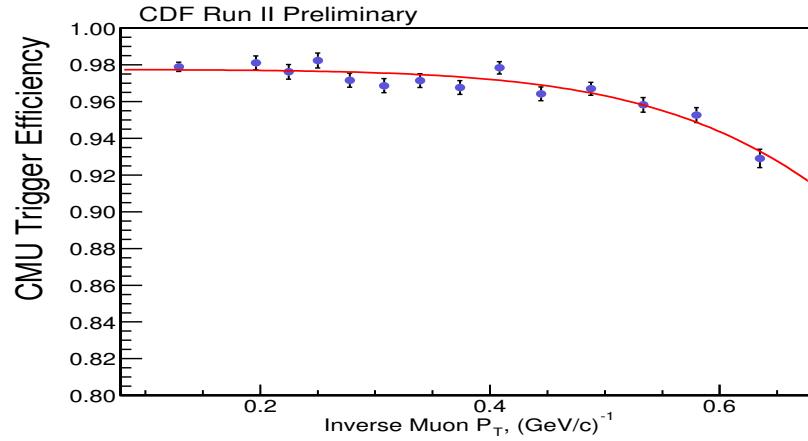
L1 Muon Trigger performance



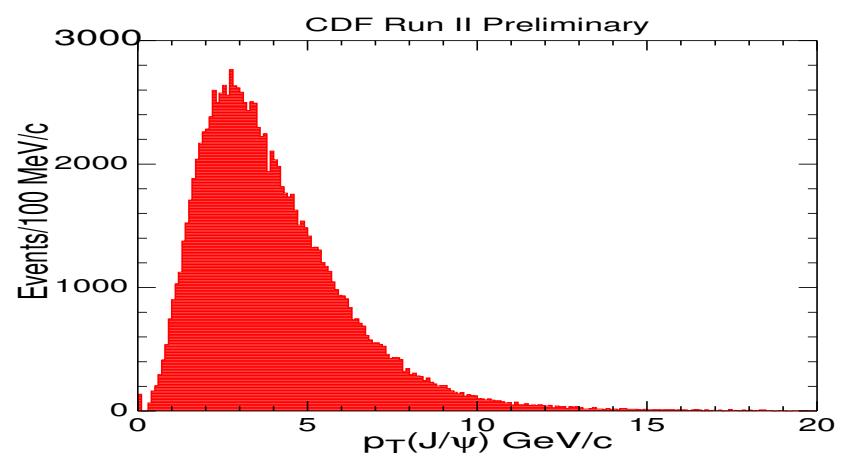
L1 track trigger (XFT) efficiency.



Inefficient near center of wire planes



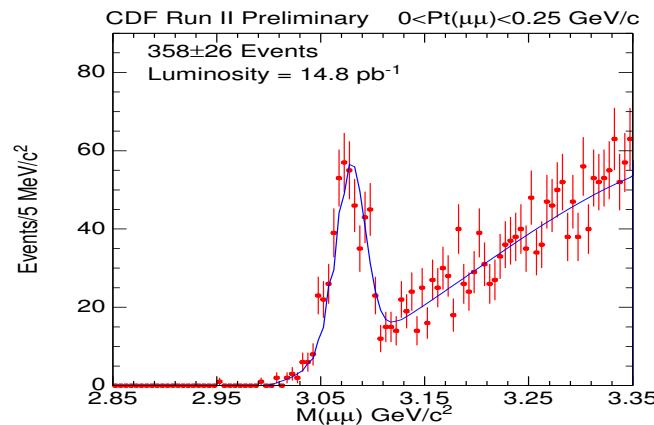
L1 μ trigger eff.



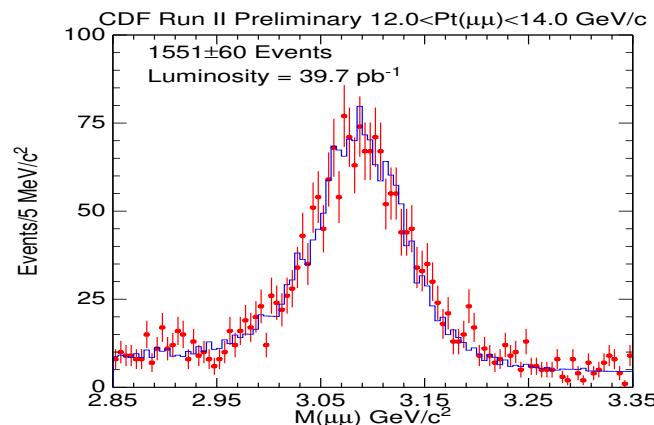
J/ψ momentum spectrum

J/ψ Reconstruction - CDF

Invariant Mass Distributions

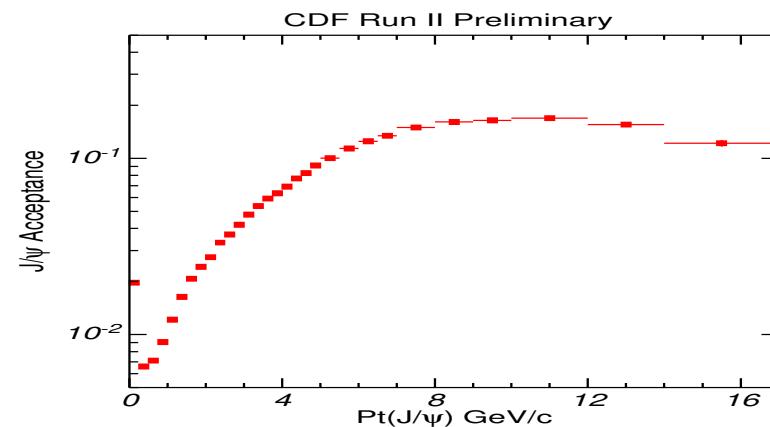


$0 < p_T(J/\psi) < 0.25 \text{ GeV}/c$

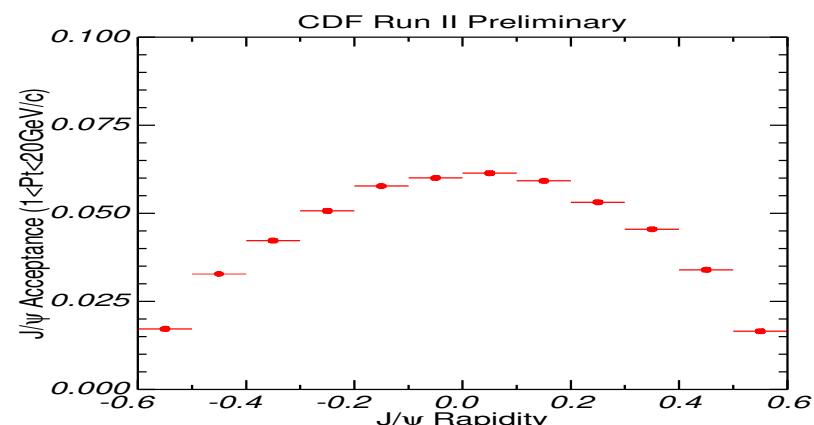


$12 < p_T(J/\psi) < 14 \text{ GeV}/c$

Detector acceptance (MC)



Transverse momentum

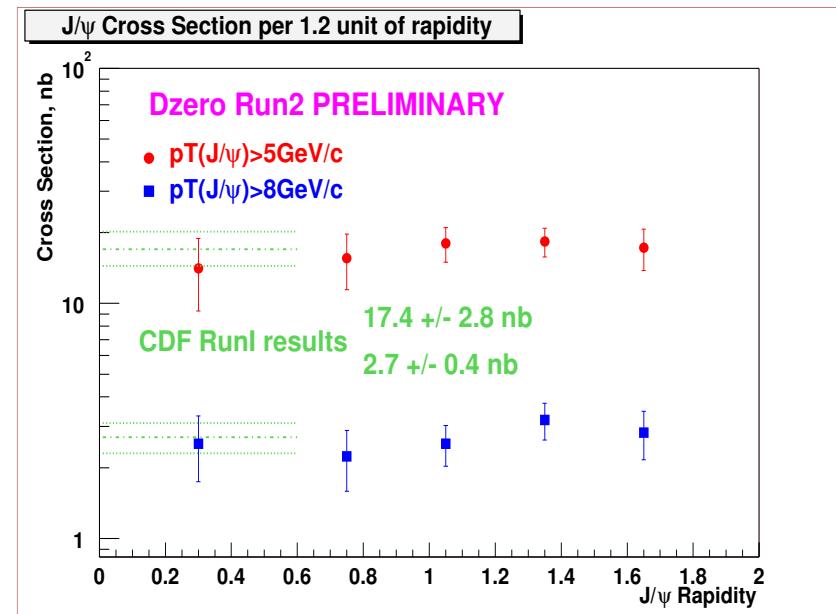
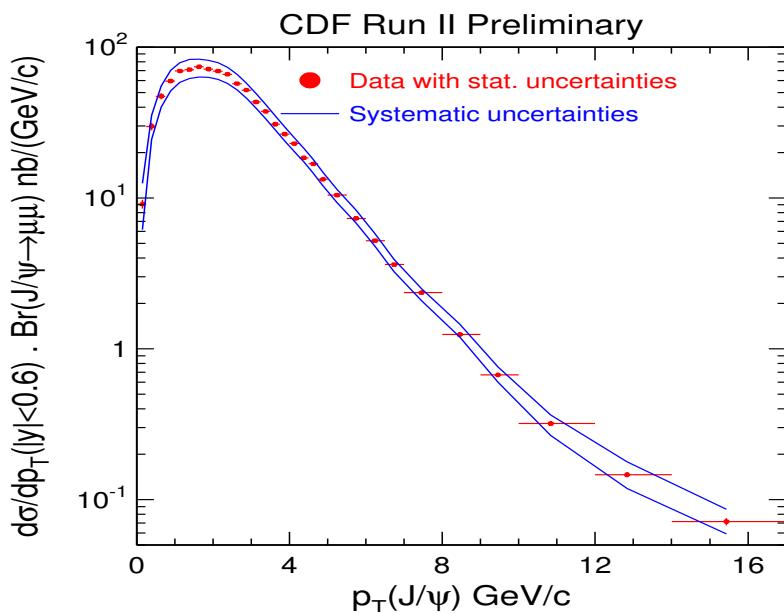


Rapidity

J/ψ Cross-sections - Run II

$$\frac{d\sigma(p\bar{p} \rightarrow J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity} \times \text{acceptance} \times \text{efficiency} \times \Delta p_T}$$

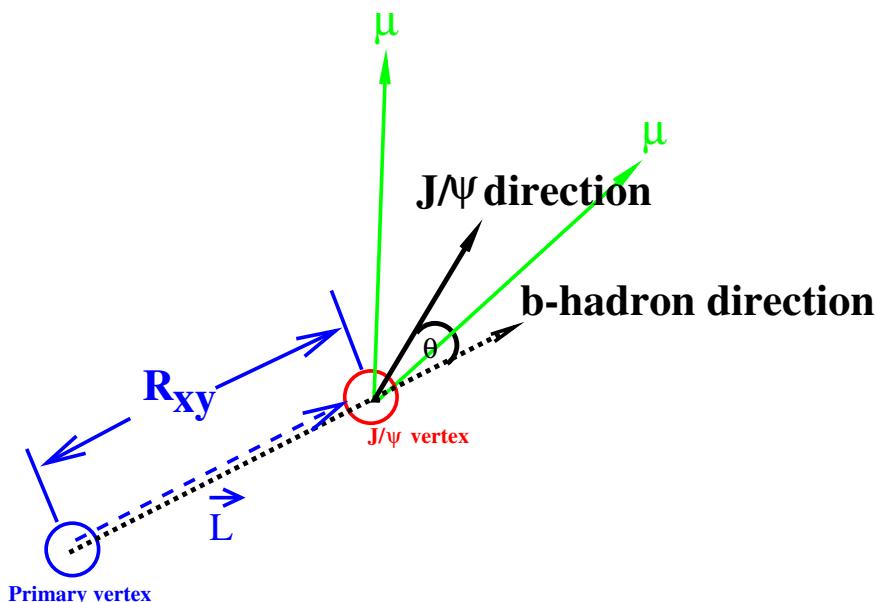
$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6)$ vs $p_T(J/\psi)$ $\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5, 8 \text{ GeV}/c)$ vs $y(J/\psi)$



$\sigma(p\bar{p} \rightarrow J/\psi X, |y(J/\psi)| < 0.6) = 4.08 \pm 0.02(\text{stat})^{+0.60}_{-0.48}(\text{syst}) \mu\text{b}$

Separate $H_b \rightarrow J/\psi X$ from Total

- The J/ψ inclusive cross-section includes contributions from
 - Direct production of J/ψ
 - Indirect production from decays of excited charmonium states such as $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$
 - Decays of b -hadrons such as $B \rightarrow J/\psi X$



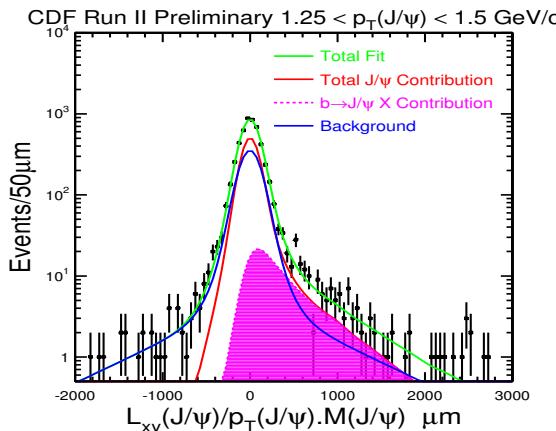
- b -hadrons have long lifetimes, J/ψ from $H_b \rightarrow J/\psi X$ will be displaced.

Extracting the J/ψ b -fraction

- A maximum unbinned likelihood fit to the **flight path** of the J/ψ in the $r - \phi$ plane, L_{xy} is used to extract the **b -fraction**.
- A MC simulation is used to model the L_{xy} distribution from $H_b \rightarrow J/\psi X$

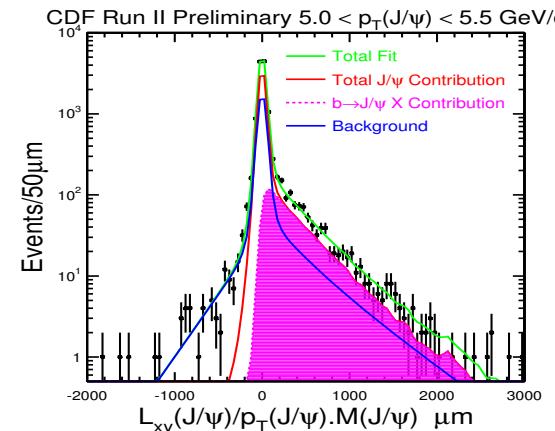
$1.25 < p_T < 1.5 \text{ GeV}/c$

$$f_b = 0.097 \pm 0.010^{+0.012}_{-0.010}$$



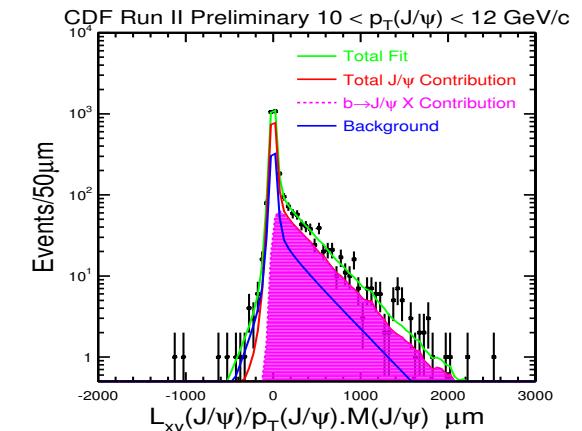
$5.0 < p_T < 5.5 \text{ GeV}/c$

$$f_b = 0.143 \pm 0.005^{+0.006}_{-0.006}$$



$10 < p_T < 12 \text{ GeV}/c$

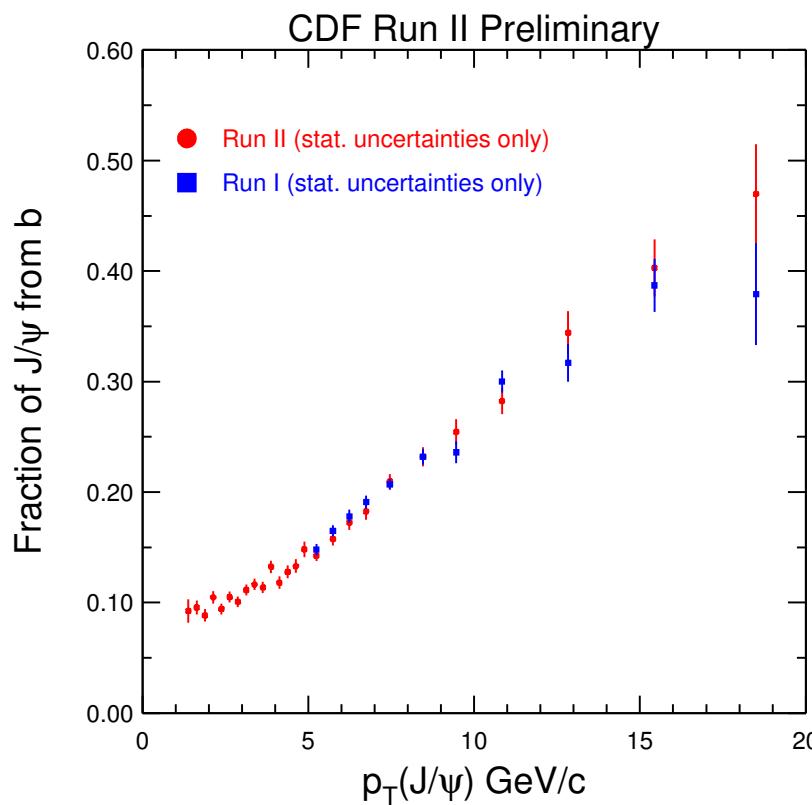
$$f_b = 0.279 \pm 0.012^{+0.008}_{-0.007}$$



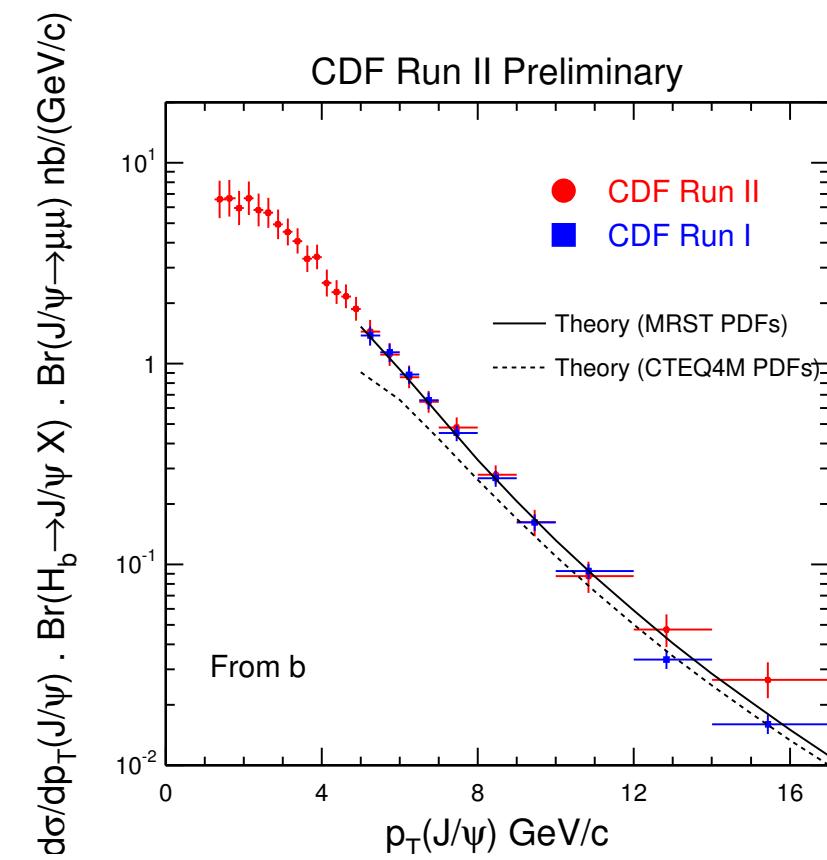
$L_{xy}(J/\psi) \cdot M(J/\psi)/p_T(J/\psi) \mu\text{m}$

$$d\sigma(p\bar{p} \rightarrow H_b X)/dp_T(J/\psi)$$

Fraction of J/ψ s from H_b



$d\sigma(p\bar{p} \rightarrow H_b X, H_b \rightarrow J/\psi X)/dp_T(J/\psi)$



Theory: J. Binnewies, Bernd A. Kniehl and G. Kramer, Phys. Rev. D58 034016 (1998).

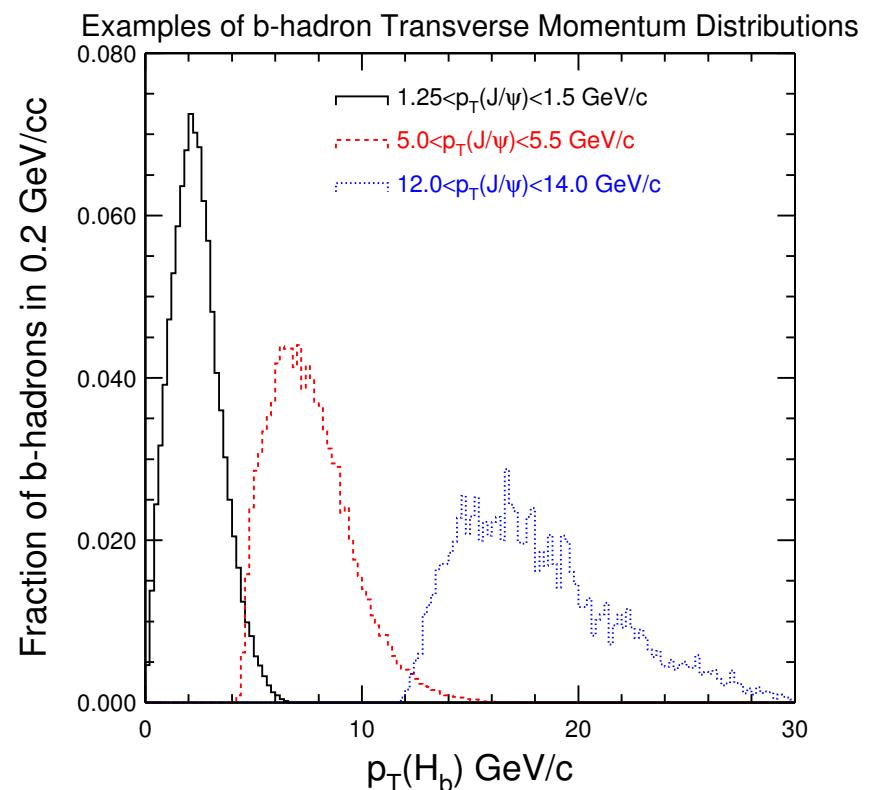
Algorithm to extract $d\sigma/dp_T(H_b)$

- Count the observed number of b -hadrons in a given $p_T(H_b)$ bin

$$N_i^b = \sum_{j=1}^N w_{ij} N_j^{J/\psi}$$

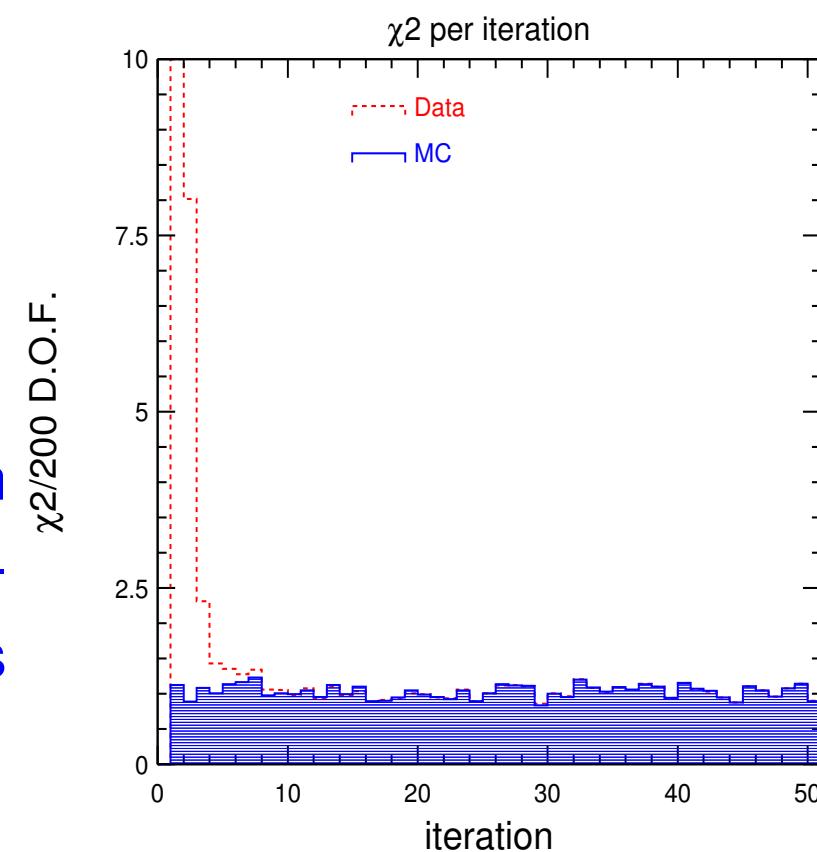
w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ bin obtained from MC.

- Correct the observed number of b -hadrons for the kinematic acceptance



Iterating...

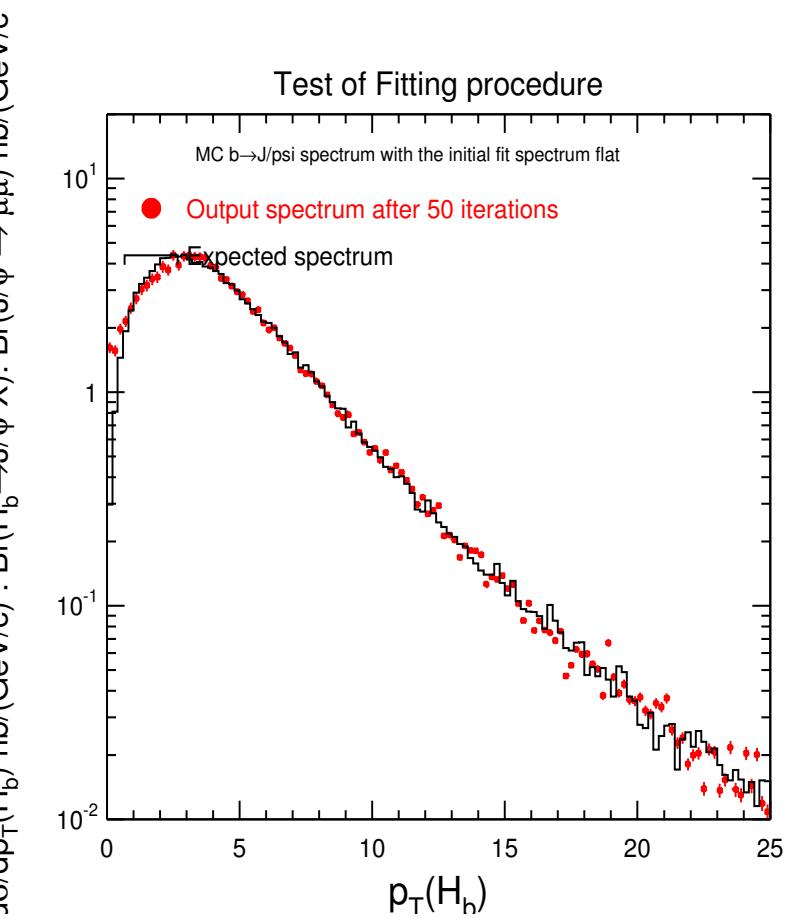
- After a $d\sigma/dp_T(H_b)$ spectrum is obtained, the MC weights w_{ij} are recomputed using the new spectrum and the algorithm repeated.
- A χ^2 test is performed on the input and output spectra until no difference is seen.



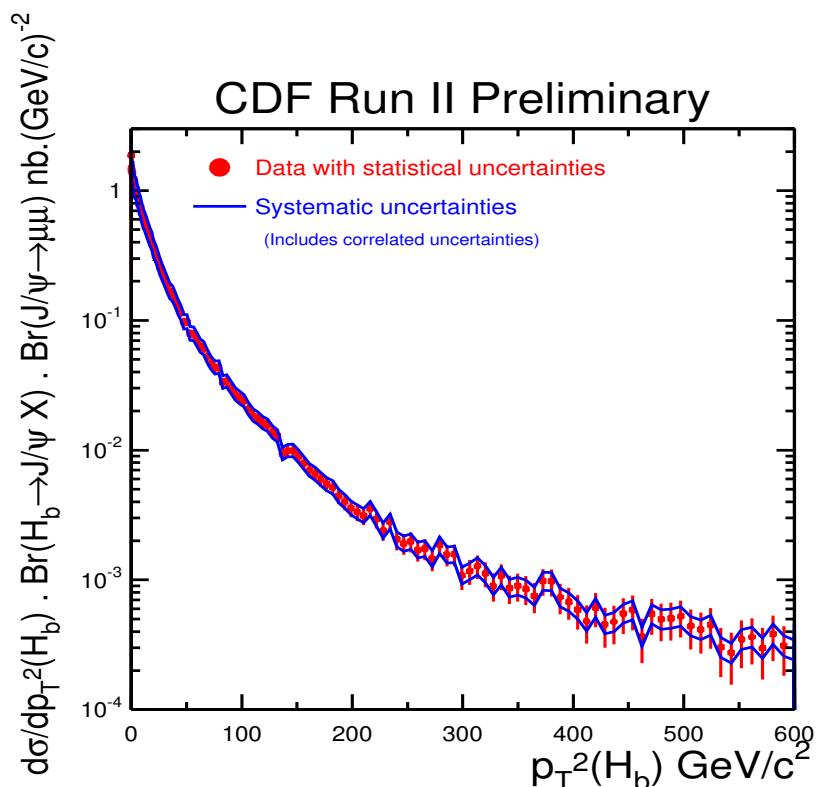
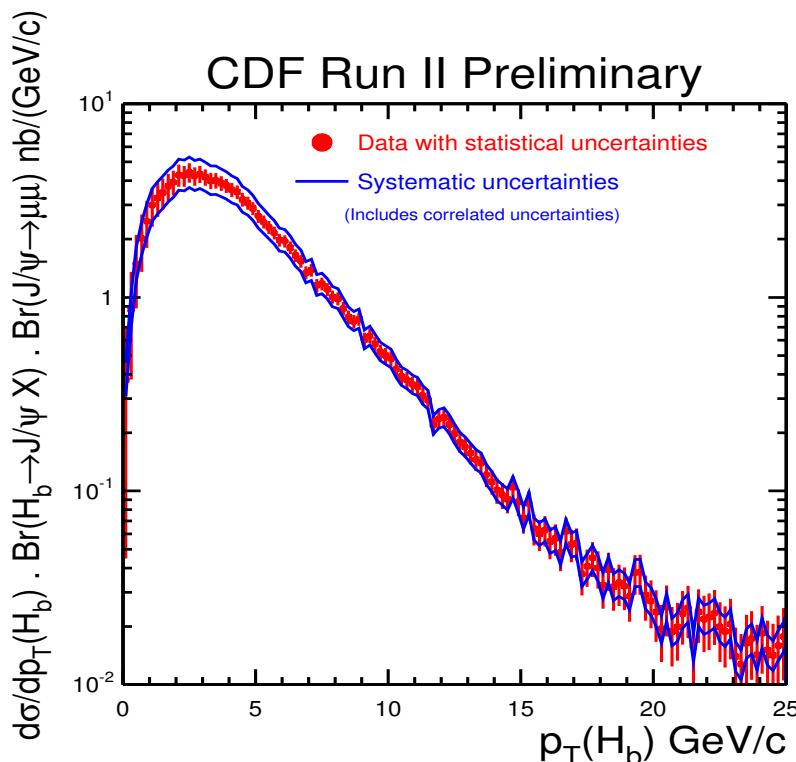
Test of Procedure

- We test the algorithm using the $d\sigma/dp_T(J/\psi)$ distribution from a MC sample with a *known* distribution of $d\sigma/dp_T(H_b)$ similar to the data.
- An *independent* MC sample, generated with a flat $d\sigma/dp_T(H_b)$ spectrum, is used to compute the weights w_{ij}

The correct spectrum is extracted.



The inclusive H_b cross-section



Since each H_b contains a bottom quark, correcting for branching fractions we get: $\sigma(p\bar{p} \rightarrow \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(syst)\mu b$

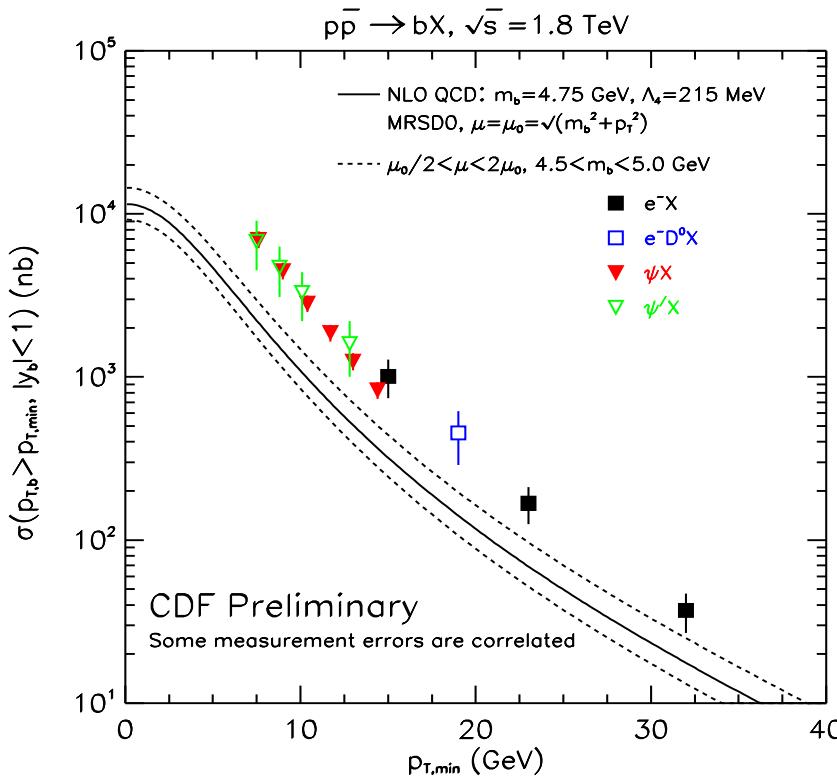
Systematic uncertainties

Source of uncertainty	Value
Uncertainties on b -fraction	
Resolution function shape (including tails)	1 – 8% (p_T dependent)
MC production spectrum	2 – 7% (p_T dependent)
MC decay spectrum	0.5 – 4% (p_T dependent)
MC b -hadron lifetime	1 – 4% (p_T dependent)
Background fit model	< 3% (p_T dependent)
Uncertainties on cross-section	
<u>Acceptance</u>	<u>9 – 16%</u> (p_T dependent)
Inclusive J/ψ cross-section	6 – 15% (p_T dependent)
Fully correlated (from inclusive)	±6.7%

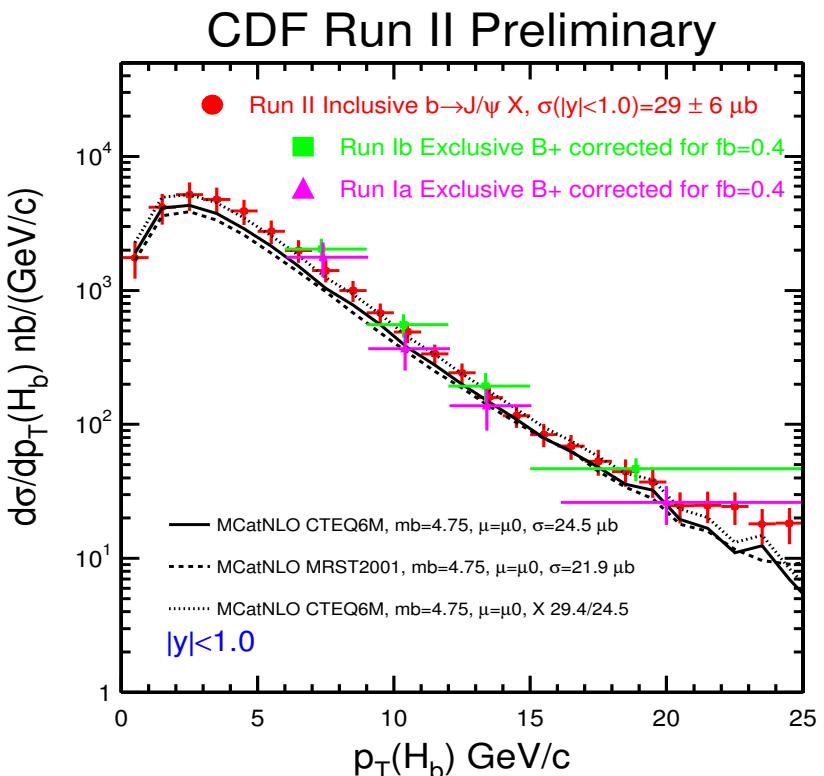
b-production x-section status

*QCD NLO at 1.96 TeV, with the latest PDFs properly matched to HERWIG
shower MC for fragmentation (MC@NLO, JHEP 0206:029,2002)*

$\sigma(p\bar{p} \rightarrow bx)$ for ($p_T > p_{T,\min}^{min}$)



$\sigma(p\bar{p} \rightarrow bx)$ versus ($p_T(H_b)$)

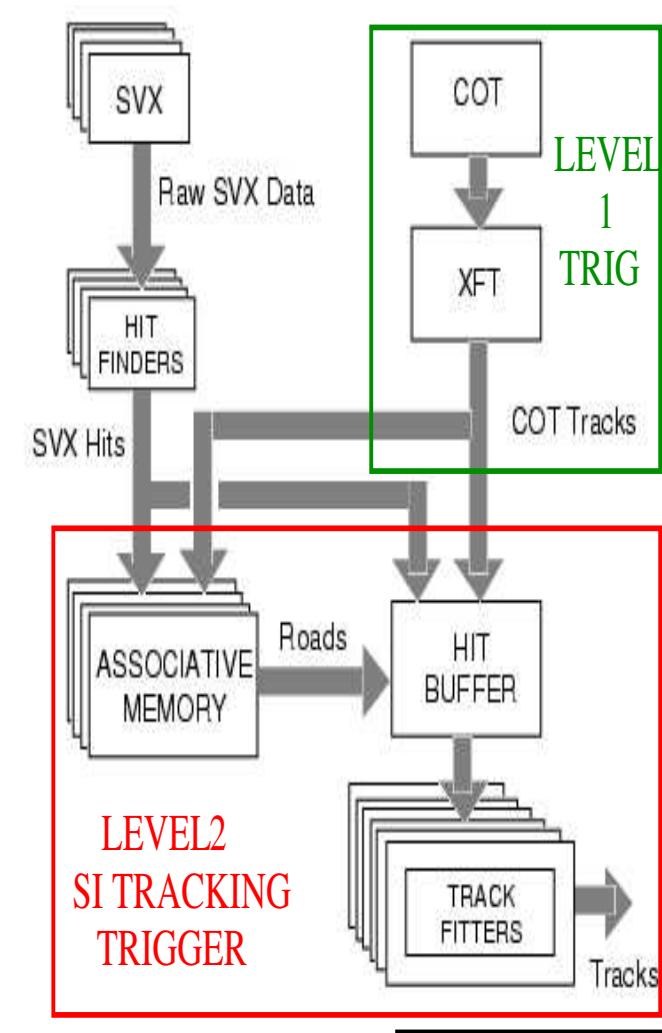
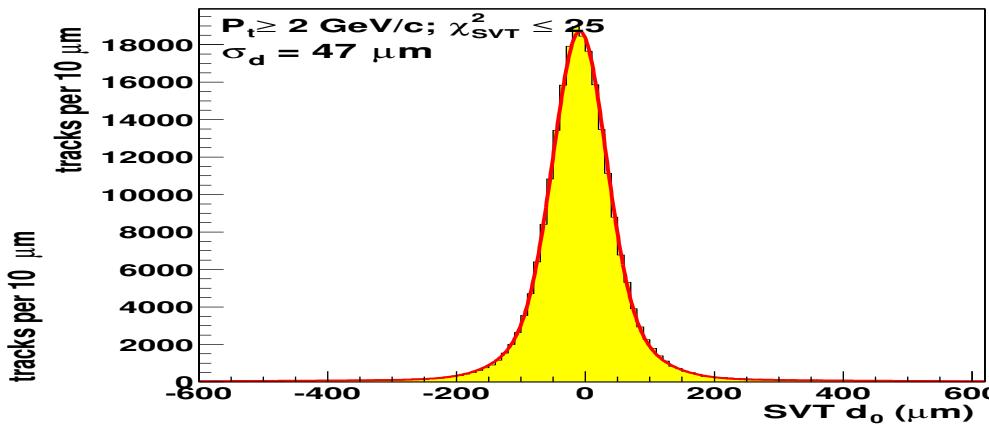
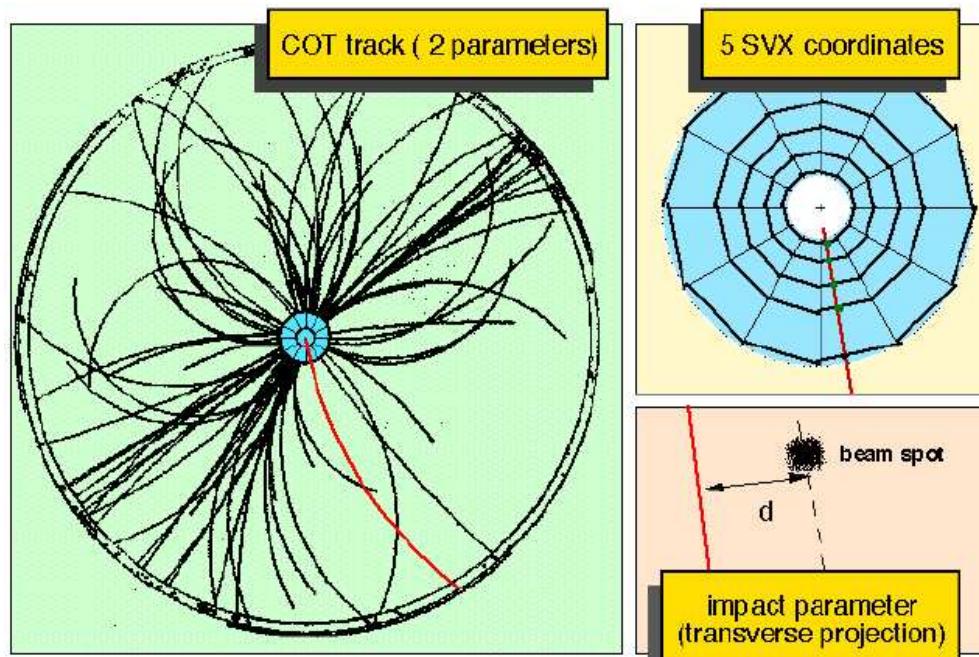


1997

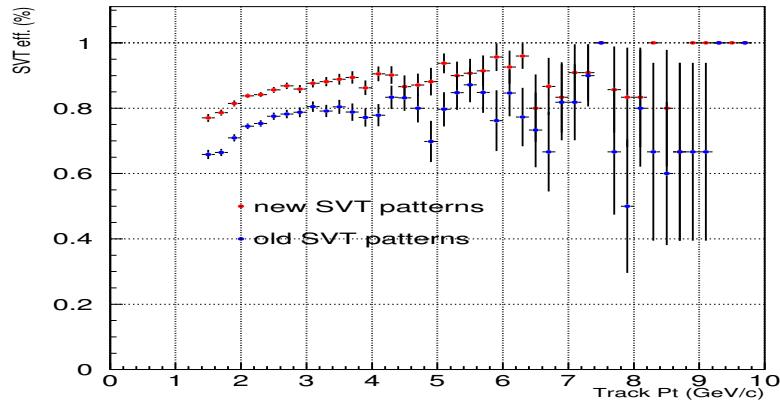
2003

CHARM MESON CROSS-SECTIONS

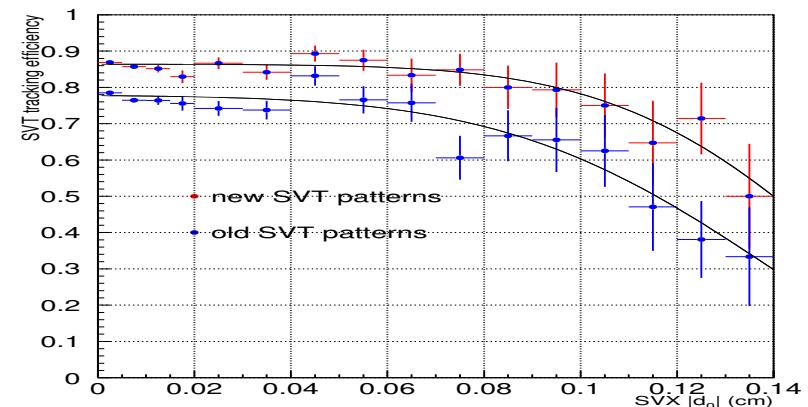
L2 Silicon Vertex Trigger (CDF)



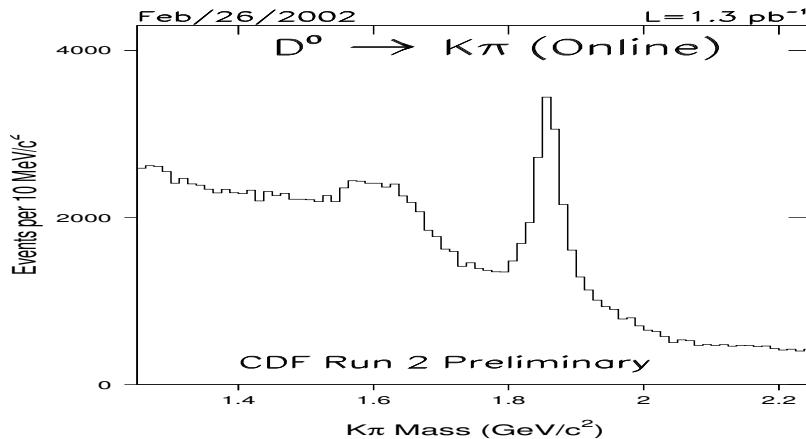
SVT Triggers on Charm



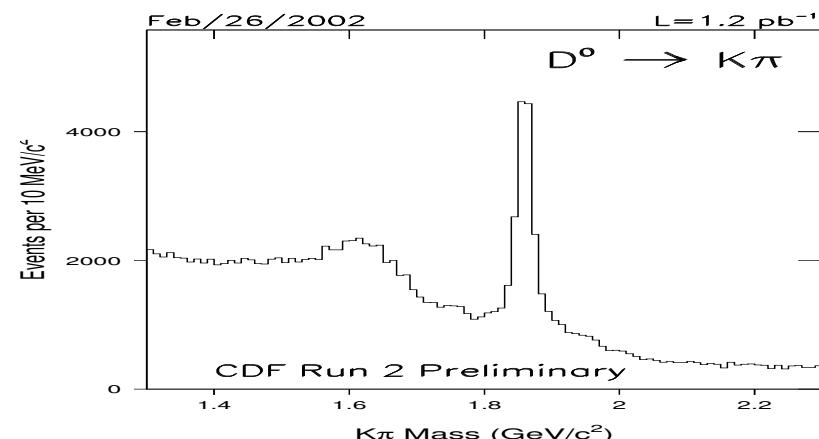
Eff. vs track p_t



SVT Eff. vs track d_0

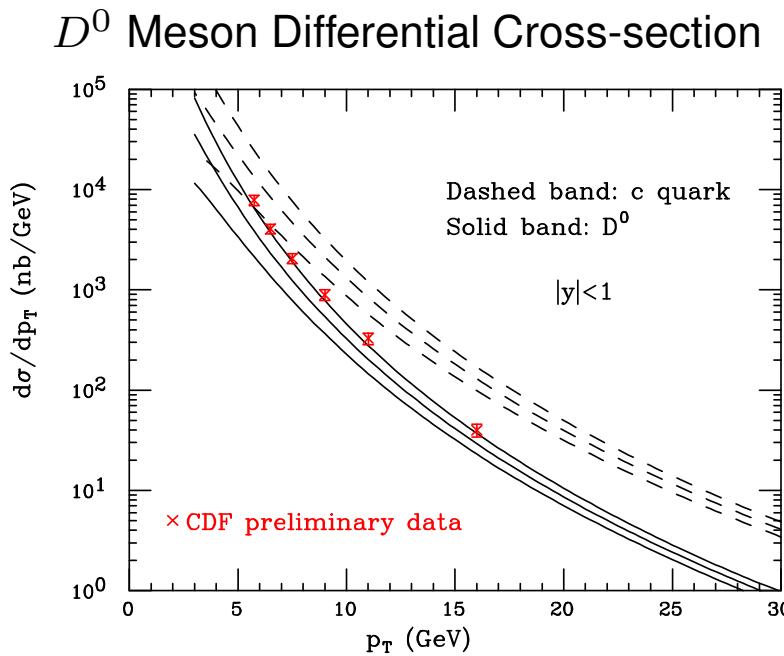


SVT + trigger info

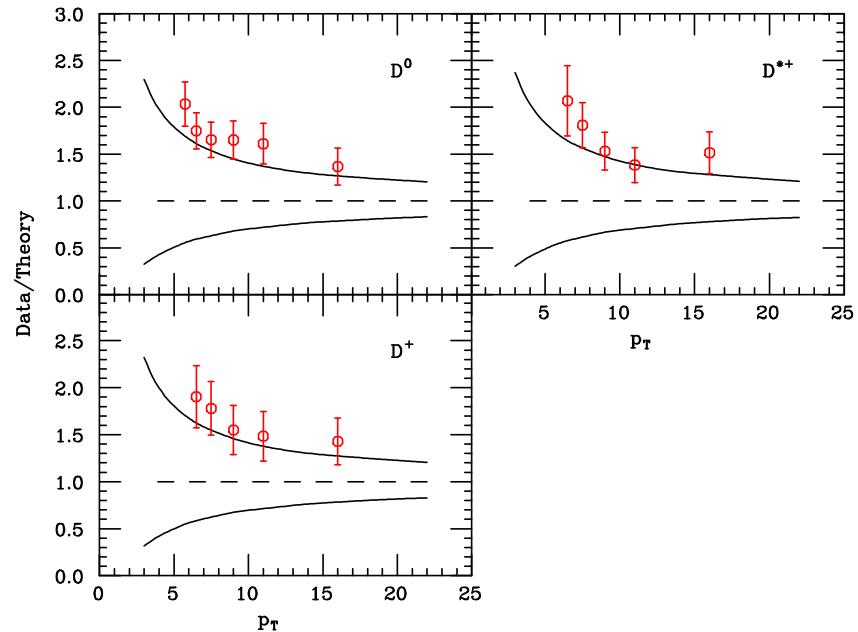


Offline reconstruction

Charm cross-sections



D Meson Cross-sections Data/Theory



M. Cacciari, P. Nason. hep-ph/0306212.

$$\sigma(p\bar{p} \rightarrow D^0 X, |y| < 1.0, p_T > 5.5 \text{ GeV}/c) = 13.3 \pm 0.2(\text{stat}) \pm 1.5(\text{syst}) \mu\text{b}$$

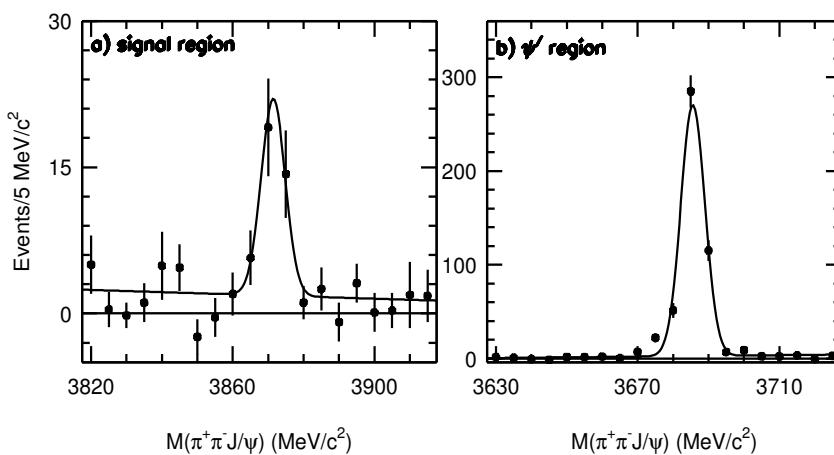
$$\sigma(p\bar{p} \rightarrow D^+ X, |y| < 1.0, p_T > 6.0 \text{ GeV}/c) = 4.3 \pm 0.1(\text{stat}) \pm 0.7(\text{syst}) \mu\text{b}$$

$$\sigma(p\bar{p} \rightarrow D^{*+} X, |y| < 1.0, p_T > 6.0 \text{ GeV}/c) = 5.2 \pm 0.1(\text{stat}) \pm 0.8(\text{syst}) \mu\text{b}$$

$$\sigma(p\bar{p} \rightarrow D_s X, |y| < 1.0, p_T > 8.0 \text{ GeV}/c) = 0.75 \pm 0.05(\text{stat}) \pm 0.22(\text{syst}) \mu\text{b}$$

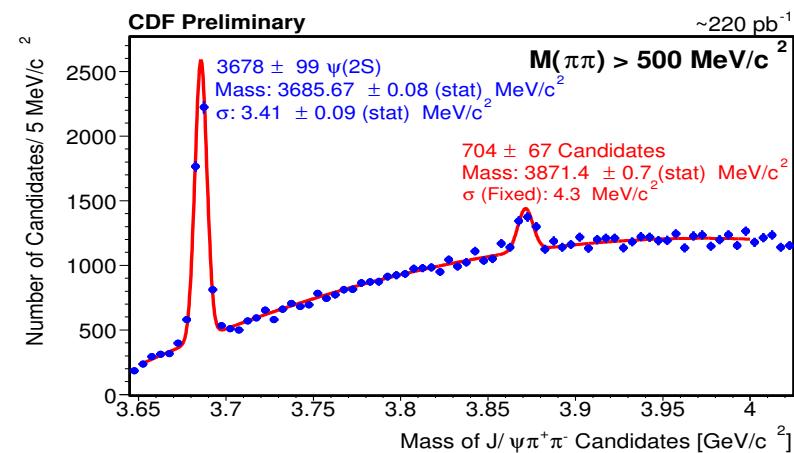
NEW: $X(3870) \rightarrow J/\psi\pi\pi$ Confirmed

- At LP 2003, the Belle collaboration announced the observation of a new state decaying into $J/\psi\pi\pi$ from analysis of B decays.



Belle

Is this a DD^* molecule?



CDF

Can CDF determine production mechanism?

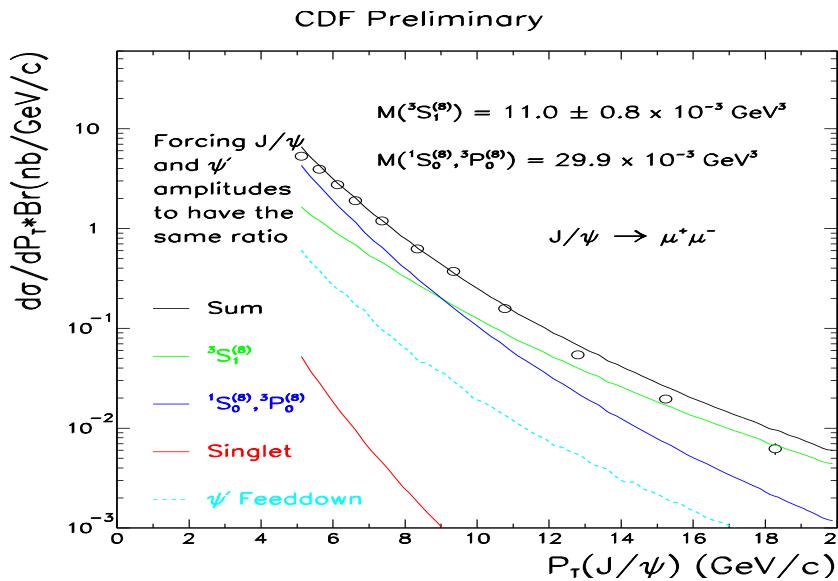
Conclusions

- Studies of heavy quark production at the Tevatron are now precision tests of QCD at NLO.
- In 2003, new measurements of the inclusive central J/ψ cross-sections and the inclusive central b cross-sections down to $p_T = 0$ GeV/c have been carried out at CDF. *These are the first measurements down to $p_T = 0$ GeV/c at a hadron collider.*
- Phenomenological fits to PDFs and the fragmentation functions from many different experiments have improved theoretical agreement with the production spectrum at the Tevatron. **Total inclusive cross-sections are in agreement with theoretical predictions within errors.**

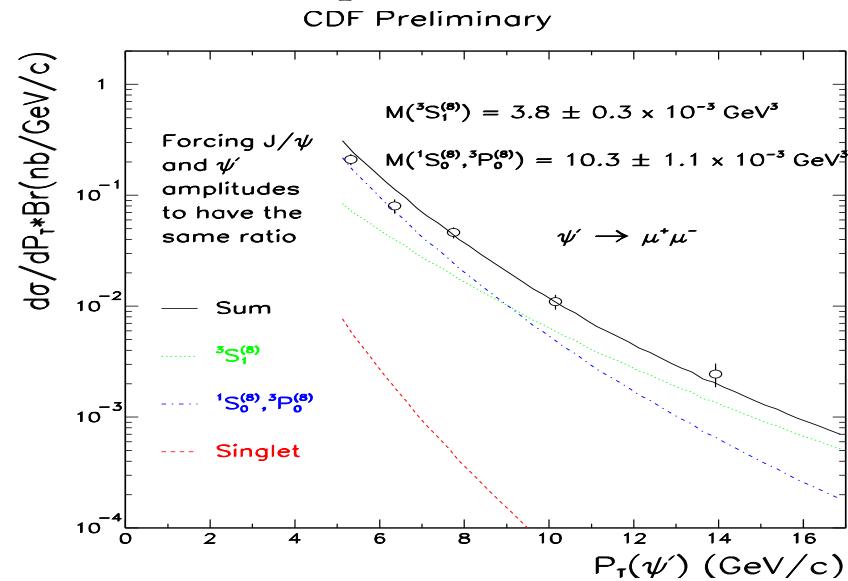
BASICS OF QUARKONIA PRODUCTION

Quarkonia Production - Theory

Quarkonia bound states are *non-relativistic*. NRQCD LO perturbative expansion is $\mathcal{O}(\alpha_s^3 v^0)$ as in the color singlet model (CSM) + higher order $\mathcal{O}(\alpha_s^3 v^4)$. *Fragmentation processes \propto color octet matrix element dominate*. Predictions agree well with data at the Tevatron at high p_t .



Direct J/ψ production (Run I)



ψ' production (Run I)

Quarkonia Production - contd

At lower p_t NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.

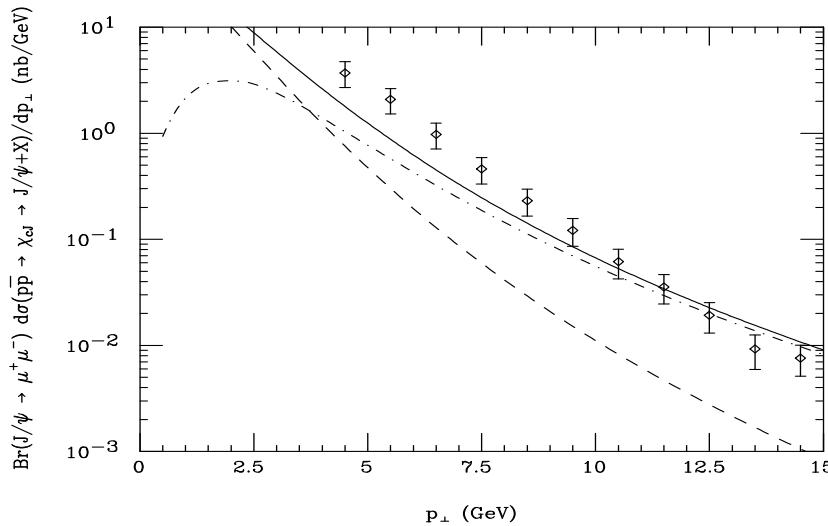
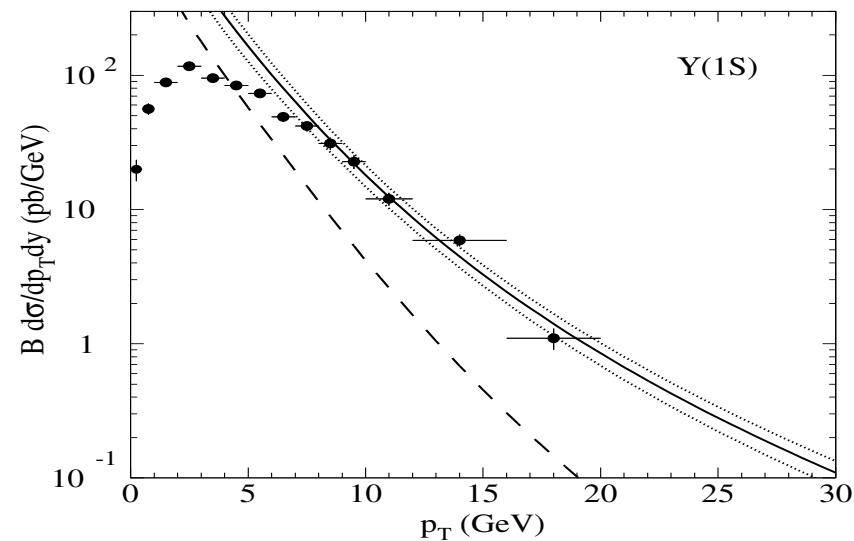


Figure 7

Direct χ_c production



$\Upsilon(1S)$ production

Recent theoretical advances in the resummation of the soft gluon effects of the color octet matrix elements for $e^+e^- \rightarrow J/\psi X$.

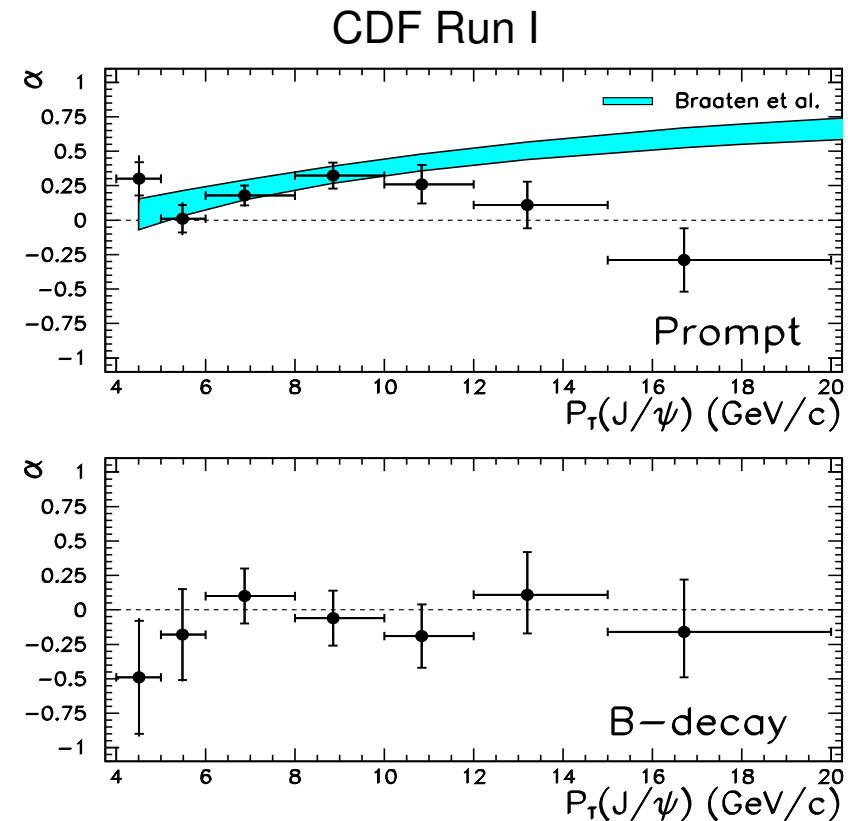
No new theoretical predictions for low p_T quarkonium at $pp\bar{p}$.

Charmonium Polarization Mystery

BUT Inclusion of color octet in NRQCD leads to a prediction of **increasing transverse polarization of charmonium at high p_t .**

Method: Fit the production angle, $\cos \theta^*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \rightarrow J/\psi X$

$$dN/d\cos \theta^* \propto (1 + \alpha \cos^2 \theta^*)$$



Run II :Need more precise measurements